ECO-FUNCTIONAL ASSESSMENT OF GROCERY SHOPPING BAGS

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CERTIFICATE OF ORIGINALITY

I hereby declare that this thesis is my own work and that, to the best of my knowledge and belief, it reproduces no material previously published or written, nor material that has been accepted for the award of any other degree or diploma, except where due acknowledgement has been made in the text.

______________________________ (Signed)

MUTHU Subramanian Senthilkannan (Name of student)

<u>Dedication</u>

This thesis is dedicated to the lotus feet of my ever beloved Lord Pazhaniandavar

And

My beloved Dad

ABSTRACT

In this environmentally conscious era, the environmental implications of any product, including textile products, are of pivotal significance. Decisions on the life of textile products are determined by the functional properties of products, which will in turn govern their ecological properties in most instances. These interlinked factors go hand in hand and very importantly they govern consumer behaviour. Functional and ecological properties combined with consumer behaviour are the key aspects influencing the implications for the environment of a product. Functional, ecological properties and consumer behaviour are currently treated as individual issues by consumers, business people and also industry. In fact, they are interrelated and also interactive with each other; their interaction is at the heart of this research. To date, no systematic study has been reported in the literature addressing the interrelation and interaction of these aspects. This study makes an attempt to combine these aspects in a single platform termed "Eco-Functional Assessment". This research discusses the concept of eco-functional assessment and demonstrates the applications of the concept by considering shopping bags used for grocery purposes as an example.

Knowledge gaps were identified by a systematic and extensive literature review in the areas pertaining to eco-functional assessment and shopping bags, specifically. The primary aim of this research is to fill the knowledge gaps by establishing a theoretical framework of eco-functional assessment, which has not been reported in the literature to date. An eco-functional assessment model was developed with four inputs (raw materials, process of manufacture, functional properties and ecological properties) and five outputs (quality, functionality, 3Rs, human impact and environmental impact).

These inputs and outputs and their interrelation can provide a profile of the essential characteristics for the eco-functional assessment of any textile product. An eco-functional assessment combined with the life cycle assessment (LCA) study was also conducted to assess the influence of functional, ecological properties and consumer behaviour on carbon footprint, ecological footprint and eco-damage throughout the life cycle of various shopping bags. Research questions were formulated to identify the contribution of each phase in the life cycle to the final life cycle impact of the shopping bags.

Beginning from raw material, since no approach or model has been reported for the quantification of various textile fibres and raw materials used for shopping bags in terms of their environmental impact and ecological sustainability, a model was created to evaluate and quantify the environmental impact index (EI) and ecological sustainability index (ESI) of different textile fibres and other raw materials used for shopping bags. From the developed model, it was found that organic cotton is the most and acrylic the least sustainable fibre.

For the process of manufacture, it is worthwhile to conduct a life cycle audit to develop a comprehensive life cycle inventory of the manufacturing process of a product from the cradle to gate stage. This research demonstrates an approach to conduct a life cycle audit in a factory that manufactures a range of nonwoven shopping bags to obtain the primary data for the production processes of different types of nonwoven bags. Life cycle impacts of the manufacturing phase of various shopping bags were quantified by characterizing and normalizing the impacts pertaining to consumers living in Mainland

China. The manual calculation results were verified with the commercial software, SIMAPRO version 7.2.

For functional properties, a comprehensive list was drawn up and evaluated in this study. With regard to shopping bags, there are some properties which lie at the interface of functional and ecological properties, which I term here the "Eco-functional properties" of shopping bags. They are: reusability, impact strength and weight-holding capacity. Currently, there are no instruments available to evaluate these properties scientifically. Hence in this research, a new instrument termed "Eco-functional Tester" was developed to quantify these properties in various shopping bags. From the experimentation results, it was clear that reusable bags made out of cotton exhibited better results in terms of eco-functional properties.

In the disposal phase of shopping bags/textile products, recyclability is one of the primary factors that need to be considered in evaluating the eco-impact. There are no models or approaches to quantify the recyclability potential of various textile fibres and raw materials used for shopping bags in terms of their environmental and economic gains. An attempt was made in this research to develop a model to quantify the recyclability potential index (RPI) of various textile fibres and raw materials used for shopping bags. Results of the RPI model indicate that polypropylene and polyester outscored all the other materials in question. Apart from reusability and recyclability, biodegradability is also an important focus in the ecological category. This research employed the results of a biodegradability test conducted for various shopping bags on the same platform using the soil burial test. Soil burial test results showed that paper bags followed by cotton bags demonstrated better biodegradation results.

Regarding consumption behaviour, the perceptions or opinions of consumers have to be taken into consideration to make the end-of-life scenario values in the life cycle assessment calculations rather than using assumptions of the usage and disposal values. LCA studies reported to date on various shopping bags have used an assumption to model the end-of-life scenarios of various shopping bags, but this may not reflect reality. Hence a questionnaire survey was conducted in this research among different user groups in Mainland China, Hong Kong and India and the results from the real users were utilized to model the end-of-life phase of the various shopping bags.

With the aid of the eco-functional model where the values from the discussed aspects are synthesized, eco-functional capacities of any product can be assessed and an “eco-functional” score can be assigned to any product. 23 samples made out of different types of shopping bags were assessed in terms of their eco-functional properties and the eco-functional score of each bag was evaluated and the results are presented. The results of the eco-functional assessment reveal the importance of every aspect of a product to meet the requirements of eco-functional assessment.

For the eco-functional assessment combined with LCA study various shopping bags, a suitable functional unit based on consumption statistics from Mainland China, Hong Kong and India was earmarked for this LCA study. Detailed life cycle inventory details were collected for various life cycle phases of different types of shopping bags. Carbon footprint, ecological footprint and eco-damage assessments were made to quantify the life cycle impacts of each phase of the various shopping bags with the aid of SIMAPRO version 7.3 of LCA software. The LCA results revealed that each phase of life cycle impacted the final result and the reusable bags outscored single use bags in all three territories. Nonwoven bags made out of polypropylene followed by polyester and woven cotton bags caused fewer life cycle impacts. LDPE bags were shown to create higher impacts in the list of samples chosen for this study. Also the life cycle impacts of shopping bags used by an average Indian were found to be less compared to those for Chinese and Hong Kong residents.

It was also apparent from the LCA results that the greater degree of reuse selected, the less the carbon footprint, ecological footprint and eco-damage in all the three territories. Even a small contribution from the consumer’s side, to reuse a bag one more time, would make a great difference in terms of mitigating environmental impact. Consumer’s support in terms of reusing a bag till its last point in life cycle and recycling it rather than disposing to landfill, supported by government recycling policies, will reduce the environmental impacts made by different types of shopping bags.

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Table of Contents

List of Figures

Page

List of Tables

Page

Glossary of Terms and Abbreviations

SIMAPRO- One of the life cycle assessment softwares developed by PRE Consultants.

SIMAPRO 7.2 version- A version of SIMAPRO used till March 2011.

SIMAPRO 7.2 version- An updated version of SIMAPRO software available to use from March 2011 onwards.

EI- Environmental impact index

ESI- Ecological sustainability index

ESIR- Ecological sustainability index rank

LCA- Life cycle assessment

LCI- Life cycle inventory

LCIA- life cycle impact assessment

3R's- Reduce, reuse, and recycle

RPI- Recyclability Potential Index

pH- Potential of hydrogen

EGI_1- Environmental Gain Index

EGI_2- Economic Gain Index

PP- Polypropylene

PET- Polyester

LDPE- Low density polyethylene

HDPE- High density polyethylene

GWP- Global Warming Potential

HTI- Human toxicity index

EII- Environmental impact index

CFPI- Carbon footprint index

ERFPI- Ecological resources footprint index

ELUI- Environmental load unit index

SI- Strength index

IRI- Impact resistance index

HSI- Human safety index

PI- Permeability index

CFI- Colour fastness index

QI- Quality index

FI- Functionality index

BI- Biodegradability index

RUI- Reusability index

RCI- Recyclability index

ECI- Ecological index

EFI- Eco-functional index

EFS- Eco-functional score

CH- Mainland China

HK- Hong Kong

IN- India

IPCC 2007- Intergovernmental Panel on Climatic Change method of carbon footprint calculation of 2007 version.

DALY- Daily adjustable life years

HH- Human health

EQ- Ecosystem quality

PDF- Potentially disappeared fraction of plant species

ISO- International organization for standardization

Chapter 1 Introduction

The number of textile products being produced for different applications every day is almost beyond quantification. Every product has a unique purpose and its journey starts with the extraction of raw materials and flows through subsequent stages such as production, transport to customers and consumption. The journey finally ends at the disposal phase. This sequence constitutes the life cycle of any product and has a detrimental impact on our living planet. Although the degree of impact varies across products in their different phases, all products have potentially negative environmental consequences. A wide mixture of textile products with different life spans can be seen in our daily life and while certain products are durable, others are thrown away even after a single use.

Textile products are characterised by an extensive list of properties: physical, chemical, functional, mechanical, comfort, physiological, bio-functional, aesthetic, ecological, thermal and so on. Some of these properties are interrelated. Decisions on the life of textile products are made by the functional properties of that particular product, which will in turn govern the ecological properties. Functional and ecological properties are intimately interlinked and they go hand in hand in deciding the ultimate fate of any textile product's useful lifetime. Amongst the various properties of textiles, although each one assumes certain importance, functional properties have gained the greatest attention, since functionality is the base on which the useful life of a product is decided.

Another property which now assumes significance almost equal to functionality is ecological properties, which relate to the life of textile products from cradle to grave. Ecological properties trace textile products through their life cycles starting from raw material extraction and finishing at the disposal stage. Ecological properties deserve our urgent attention, as we are facing terrifying environmental issues all around the globe. The environmental impact made by various products needs immediate consideration in terms of quantifying the impacts and their effects on the environment.

Under these circumstances, it is vital to essentially consider functional and ecological properties together. This research attempts to combine both functional and ecological properties in a single platform, which I term here as "eco-functional properties". Another rationale behind the concept of linking these two types of properties is that they are very much interrelated in the sense that the functionality of a product governs its ecological properties. There are numerous ways to link these properties. For instance, a product that assumes better functionality delays its disposal and the arrival of another similar but new product using raw materials, energy, manpower, chemicals, etc and also delays the disposal issues of the new product. This study explains many such links between these two properties in detail.

A widely used tool for assessing the environmental impact of products is the "Life Cycle Assessment (LCA)", an analytical tool which can help in understanding environmental impacts from the acquisition of raw materials to final disposal (SETAC, 1993; Fava et al., 1991). According to ISO 14040 and 14044 standards, LCA is conducted in four stages, i.e. goal and scope definition, life cycle inventory, life cycle impact assessment and life cycle interpretation (ISO 14040, 2006; ISO 14044, 2006).

Shopping bags are an inevitable feature of every individual's life. One needs shopping bags primarily for carrying groceries from supermarkets to home, along with the other functions for which they are intended. There are different types of shopping bags to cater for different shopping needs. A variety of raw materials and technologies are employed to manufacture them. The most popular are plastic, paper, nonwoven and woven bags, with plastic and paper bags mainly intended for single use and nonwoven and woven ones being reusable.

Shopping bags are professed to be a symbol of the throw-away society, exacerbating the seriousness of their environmental impact. Most nations are seriously thinking of addressing the littering issues created by shopping bags and they are occupying a significant position in any country's green agenda. Most nations are attempting to alleviate the environmental impact posed by shopping bags. Current environmental activities include plastic bag reduction campaigns, plastic bag levies, and promotion of reusable bags. Shopping bags are one of the essential articles that need to be evaluated in terms of their eco-function in the modern context, where everyone is well aware of the vital issues associated with them.

The concept of "eco-functionality" is an uncharted area of research to date and this study aims to explore the concept and its applications. The performance of any product on the eco-functional front is of significant importance in the current scenario. This research primarily revolves around the creation of an "eco-functional" model, from which the eco-functional capabilities of any product can be assessed and an "eco-functional" score/grade can be assigned to any product. Considering shopping bags as base materials, the concept of "eco-functional" proposed in this study is investigated.

Shopping bags made out of plastic (high and low density polyethylene), paper, nonwoven (polypropylene and polyester) and woven (cotton) bags will be evaluated for their eco-functional properties and the eco-functional scores of each category are recorded and assessed. Framework of this thesis is depicted in flow chart form in Fig.1-1.

This thesis also presents the findings of an extensive literature review and identifies the knowledge gaps in Chapter 2. Chapter 2 also discusses the objectives, the research methodology adopted and the significance and originality of the study.

Chapter 3 deals with the development of a theoretical framework of "eco-functional assessment", which includes selection of different inputs and outputs and their interrelations to achieve the desired "eco-functional" value/score of any textile product/shopping bag. It also includes comprehensive details of the life cycle assessment model and deals with the various research questions to be tested by this theoretical framework.

The next four chapters are designed to represent the life cycle of textile products/shopping bags. Each chapter is devoted to collecting the life cycle inventory (LCI) data pertaining to each stage of the entire life cycle from raw material extraction to disposal. The next chapter, Chapter 4 deals with the LCI of the raw material stage and the development of a unique model to quantify the environmental impact and ecological sustainability for different textile fibres and other raw materials used for shopping bags to embody the raw material phase of a life cycle.

Chapter 5 deals with the production phase of shopping bags/textile products. It includes the LCI of the production phase of different shopping bags using primary and as well secondary data. Life cycle impact assessment calculations for different shopping bags using the impact assessment figures specifically pertaining to China is also discussed in this chapter.

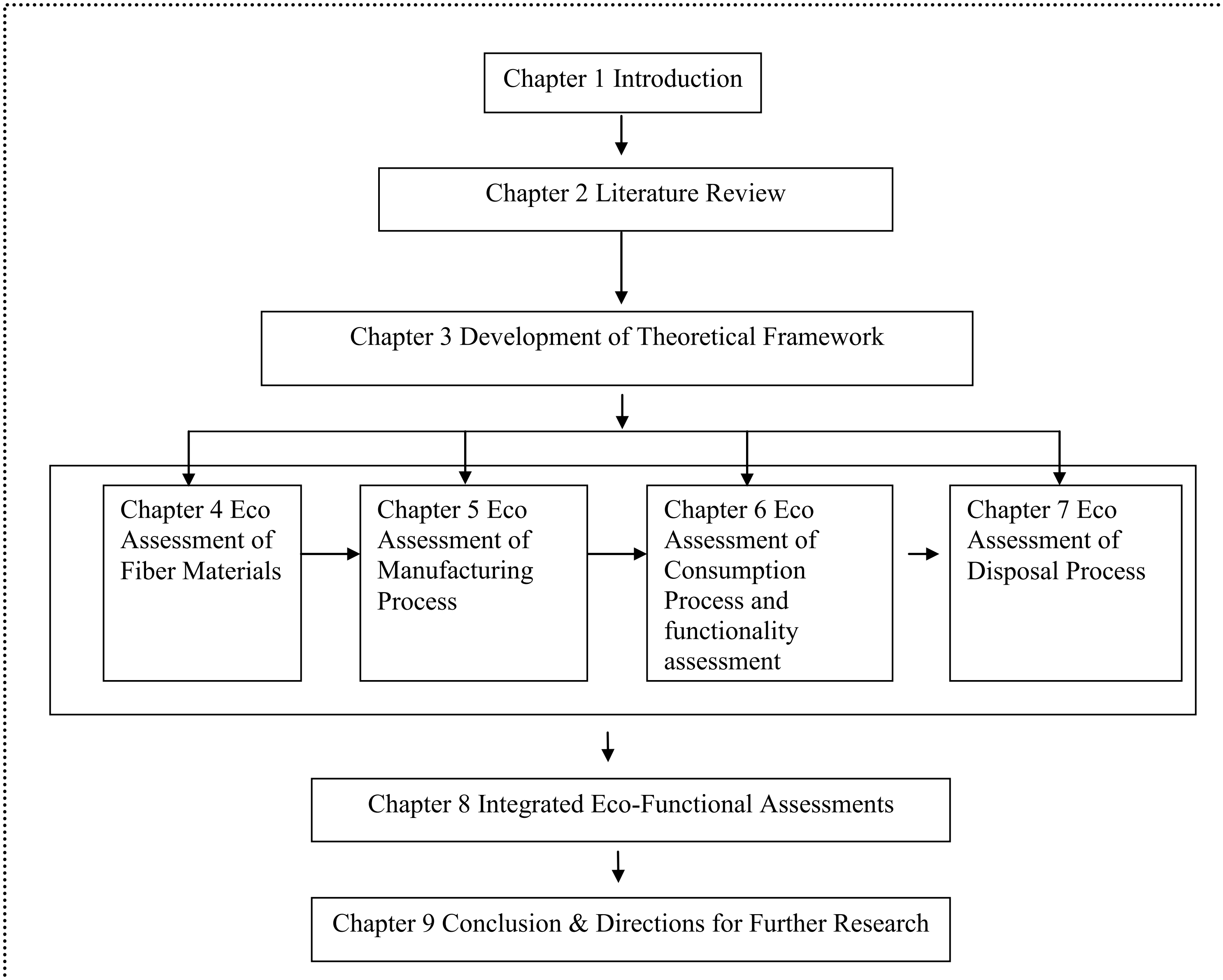


Figure 1-1 Flowchart of thesis framework

Chapter 6 encompasses the assessment of various functional properties of different types of shopping bags and also the use phase (consumption phase) of shopping bags. Data on consumer behaviour in terms of use and disposal of different shopping bags were collected from different user groups of shopping bags from Mainland China, Hong Kong and India. Also this chapter discusses the development of an eco-functional tester to quantify scientifically the reusability, impact strength and weight-holding capacity of different shopping bags. Altogether with these elements, this chapter forms a LCI for functional properties and consumption phase of different shopping bags.

Chapter 7 exemplifies the disposal phase of shopping bags/textile products, in other words, it deals with the ecological properties of shopping bags/textile products. This chapter includes a model developed to quantify the recyclability potential index for different textile fibres and other raw materials used for shopping bags, and reviews the biodegradation studies conducted on various shopping bags. With these two focuses, the chapter forms the LCI for the disposal phase of different shopping bags.

Chapter 8 consists of the assessment of the "eco-functional" properties of various shopping bags under consideration in current research and also the carbon and ecological footprint assessments, and eco-damage assessment from the LCI developed in the previous four chapters. Chapter 9 draws conclusions and explains the scope for further research.

Chapter 2 Literature Review

2.1. Introduction

This chapter discusses the status of the relevant literature in terms of functional and ecological aspects of textile products (sections 2.2.1-2.2.3), tools to assess the environmental impact of various products (section 2.2.3.3.), impact of textile processes on the environment and people (section 2.2.4), the concept of life cycle assessment (section 2.2.5), sustainable development and environmental assessment of textiles (section 2.2.6), shopping bags (types (section 2.3.1), details of production processes (section 2.3.2), life cycle assessment (section 2.3.3) and test methods (section 2.3.4)). An extensive body of literature was reviewed for this study and the knowledge gaps in the above areas were identified (section 2.4), based on which objectives are formed (section 2.5) and the research methodology is developed (section 2.6), which are dealt in this chapter. This chapter discusses the knowledge gaps identified and also critically appraises the significance and originality of the present study.

2.2. Eco- functional Assessment

2.2.1 Definition

An eco-functional assessment is defined as a methodology to assess a textile material or product in terms of both functionality and environmental implications. In other words, a textile product or any product needs to fulfil the requirements of its functionality but at the same time satisfy the requirements of the environment.

2.2.2 Aspects of eco-functional assessment - Functional aspects

As stated earlier, the concept of eco-functional assessment is derived from the ecological and functional properties of textile materials or products. The functional properties/aspects of a textile can be defined as the properties related to the function of the textile product for which it is intended. Functional properties assume significant importance, since they decide on the useful life of the product. Major functional properties which need to be considered in evaluating textile products are described below.

A. Material composition

A wide range of fibres and combination of fibres are generally employed to manufacture textiles and it is of great importance to identify the composition of particular textiles. It is a legal requirement for the manufacturer to identify and label a material's composition. This is also termed "Fibre identification"/ "Fibre content or composition determination"/ "Fabric composition determination". There are many existing methods to identify fibre/material composition and all help us to identify the type of fibre in the material being tested (Zhong and Xiao, 2008; Taylor, 1990):

1. Microscopical examination of the longitudinal and cross-sectional views of the fibre (Optical Test)
2. Burning test
3. The use of solvents and other chemical tests
4. Staining test
5. Fibre density

6. Miscellaneous methods such as melting point determination, etc

These methods can determine the composition of single layer fabrics. It is increasingly difficult, however, to find only single layer fabrics in the market. In today's greatly developed and advanced market, highly engineered fabrics are more common, including, industrial fabrics, technical fabrics made from high-performance fibres, multilayer fabrics with different combinations of materials such as nonwovens, wovens, films and paper, phase change fabrics and electrically conductive fabrics (Zhong and Xiao,2008). Testing of these sophisticated fabrics demands new instruments and methods to analyse the material composition more accurately than the existing used to date.

Traditional methods described above [1-6] assist in finding out only the fibre content, but this will not suffice to cope with the pace of green consumerism. Test methods for fibre composition must also help to analyse the products from the perspective of environmental impact assessment as well as by incorporating eco-testing features to analyse banned azo colourants, formaldehyde content, heavy metal residues, ozone-depleting chemicals, pesticide residues and so on (Zhong and Xiao, 2008). These requirements stipulate new methods for material composition tests which are discussed below. Based on these requirements, many new methods have been developed for testing fibre composition, including, but not limited to:

1. Environmental scanning electron microscope (ESEM) technology
2. Near infrared spectral image measurement system
3. Capillary electrophoresis/mass spectrometry (CE/MS) technique
4. Thermogravimetry (TG) analysis

5. Computer image processing technology (Zhong and Xiao, 2008).

Standards for material composition test

Many standards have also been developed for the material composition test. Some of the familiar and widely adopted ones include:

1. AATCC Test Method 20A-2007: Fibre Analysis: Quantitative

2. AATCC Test Method 20-2007: Fibre Analysis: Qualitative

3. ASTM D276: Standard Test Methods for Identification of Fibers in Textiles

4. ISO 1833: Textiles — Quantitative chemical analysis

    1. ISO 1833-1:2006 -- Part 1: General principles of testing
    2. ISO 1833-3:2006 Part 2: Ternary fibre mixtures
    3. ISO 1833-3:2006 - -- Part 3: Mixtures of acetate and certain other fibres (method using acetone
    4. ISO 1833-4:2006 -Part 4: Mixtures of certain protein and certain other fibres (method using hypochlorite)
    5. ISO 1833-5:2006 Part 5: Mixtures of viscose, cupro or modal and cotton fibres (method using sodium zincate)
    6. ISO 1833-6:2007 Part 6: Mixtures of viscose or certain types of cupro or modal or lyocell and cotton fibres (method using formic acid and zinc chloride)
    7. ISO 1833-7:2006 Part 7: Mixtures of polyamide and certain other fibres (method using formic acid)
    8. ISO 1833-8:2006 Part 8: Mixtures of acetate and triacetate fibres (method using acetone)
    9. ISO 1833-9:2006 -- Part 9: Mixtures of acetate and triacetate fibres (method using benzyl alcohol)
    10. ISO 1833-10:2006 -- Part 10: Mixtures of triacetate or polylactide and certain other fibres (method using dichloromethane)
    11. ISO 1833-11:2006 -- Part 11: Mixtures of cellulose and polyester fibres (method using sulfuric acid)
    12. ISO 1833-12:2006 -- Part 12: Mixtures of acrylic, certain modacrylics, certain chlorofibres, certain elastanes and certain other fibres (method using dimethylformamide)

13. ISO 1833-13:2006 -- Part 13: Mixtures of certain chlorofibres and certain other fibres (method using carbon disulfide/acetone)
14. ISO 1833-14:2006 -- Part 14: Mixtures of acetate and certain chlorofibres (method using acetic acid)
15. ISO 1833-15:2006 -- Part 15: Mixtures of jute and certain animal fibres (method by determining nitrogen content)
16. ISO 1833-16:2006 -- Part 16: Mixtures of polypropylene fibres and certain other fibres (method using xylene)
17. ISO 1833-17:2006 -- Part 17: Mixtures of chlorofibres (homopolymers of vinyl chloride) and certain other fibres (method using sulfuric acid)
18. ISO 1833-18:2006 -- Part 18: Mixtures of silk and wool or hair (method using sulfuric acid)
19. ISO 1833-19:2006 -- Part 19: Mixtures of cellulose fibres and asbestos (method by heating)
20. ISO 1833-20:2009 -- Part 20: Mixtures of elastane and certain other fibres (method using dimethyl acetamide)
21. ISO 1833-21:2006 -- Part 21: Mixtures of chlorofibres, certain modacrylics, certain elastanes, acetates, triacetates and certain other fibres (method using cyclohexanone)

B. Functional properties

The next important category of functional aspects is the functional properties of textiles, which include a long list of test methods to assess physical and dimensional characteristics as well as mechanical properties, etc. Many kinds of tests are available for testing functional properties, including, but not limited to: 1. Weight; 2. Thickness; 3. Tensile strength; 4. Tear strength; 5. Bursting strength; 6. Seam strength and slippage; 7. Permeability tests; 8. Colour fastness tests; 9. Water and oil proof tests.

The different testing standards, testing equipment and methods used are described in Table 2-1.

Test	Testing equipment/s used	Standards
Weight	Weighing Balance	• ASTM D3776/ D3776M - 09a Standard Test Methods for Mass per Unit Area (Weight) of Fabric • ISO 3801-1977- Textiles- Woven fabrics - Determination of mass per unit length and mass per unit area • ISO 9073-1:1989: Textiles -- Test methods for nonwovens -- Part 1: Determination of mass per unit area
Thickness	Thickness tester	• ISO 9073-2 - Textiles. Test methods for nonwovens. Part 2: determination of thickness. • ASTM D 1777 – 96 - Standard Test Method for Thickness of Textile Materials • ASTM D 5729 – 97 - Standard Test Method for Thickness of Nonwoven Fabrics • ISO 5084 – 1996- Textiles -- Determination of thickness of textiles and textile products
Tensile Strength and Elongation	Tensile testing machines of CRE/ CRL/CRT principles	• ISO 13934-1:1999 Textiles: Tensile properties of fabrics- Part 1: Determination of maximum force and elongation at maximum force using the strip method • ISO 13934-2:1999 Textiles: Tensile properties of fabrics - Part 2: Determination of maximum force using the grab method • ASTM D5034 - 09 Standard Test Method for Breaking Strength and Elongation of Textile Fabrics (Grab Test) • ASTM D5035 - 06(2008)e 1 Standard Test Method for Breaking Force and Elongation of Textile Fabrics (Strip Method) • ISO 9073-3:1989: Textiles -- Test methods for nonwovens -- Part 3: Determination of tensile strength and elongation
Tear Strength	Elmendorf tester/ Tensile tester (CRE) depending upon the testing standard	• ISO 4674-1998, part 1: Determination of tear resistance • ISO 13937-3-2000 Textiles - Tear properties of fabrics: Part 3: Determination of tear force of wing-shaped test specimens • ISO 13937-1-2000 Textiles - Tear properties of fabrics : Part 1:Determination of tear force using the ballistic pendulum method (Elmendorf) • BS 3424 Method 7C, Single tear, 1973 • EN 1875-3 Determination of tear resistance: Part 3: Trapezoid tear, 1997 • ASTM D1423-83 Tear resistance of woven fabrics by falling pendulum (Elmendorf) • ASTM D751 Tack tear, 1995 • ASTM D751 Puncture resistance, 1995 • ISO 5473 Determination of crush resistance, 1997 • ASTM D 5734 Standard Test Method for Tearing Strength of Nonwoven Fabrics by Falling-Pendulum (Elmendorf) Apparatus • ASTM D 5735 Standard Test Method for Tearing Strength on Nonwoven Fabrics by the Tongue (Single Rip) Procedure (Constant- Rate-of-Extension Tensile Testing Machine) • ISO 9073-4:1997- Textiles -- Test methods for nonwovens -- Part 4: Determination of tear resistance
Bursting	Ball burst tester /	• ISO 3303-1995 Determination of bursting strength

Strength	Diaphragm Bursting Strength Tester	• ISO 2960 Textiles - Determination of bursting strength and bursting distension - Diaphragm method • BS 4768 Method for determination of the bursting strength and bursting distension of fabrics • BS 3424 Methods of test for coated fabrics - Wounded burst test • ASTM D3787 Standard test method for bursting strength of knitted goods - constant-rate-of-traverse (CRT) ball burst test • ASTM D3786 / D3786M - 09 Standard Test Method for Bursting Strength of Textile Fabrics—Diaphragm Bursting Strength Tester Method • ISO 13938-2:1999 - Textiles -- Bursting properties of fabrics -- Part 2: Pneumatic method for determination of bursting strength and bursting distension
Seam strength and slippage	Tensile Tester of CRE type	• ASTM D1683 Standard test method for failure in sewn seams of woven fabrics, 1990 • ASTM D751 Seam strength, 1995 • BS 3320:1988 Method for determination of slippage resistance of yarns in woven fabrics: Seam method.
Permeability tests	1.Air permeability tester 2.Water vapour permeability tester 3.Water repellency and water resistance testers (Impact penetration tester/ Spray Tester/ Bundesmann rain tester/ Hydrostatic Pressure Tester)	• ASTM D737 – 04 (2008) Standard Test Method for Air Permeability of Textile Fabrics • ISO 9073-15:2007: Textiles -- Test methods for nonwovens -- Part 15: Determination of air permeability • ISO 9237:1995 - Textiles -- Determination of the permeability of fabrics to air -- • ASTM E96-00 • ASTM D6701-01 Standard Test Method for determining Water Vapour Transmission Rates through nonwoven and plastic barriers (Withdrawn) -- • AATCC test method 70-2000 Water repellency: Tumble jar dynamic absorption test • AATCC Test Method 22, Water Repellency: Spray Test • AATCC Method 21, Water repellency: Static absorption test • ISO 18695:2007: Textiles -- Determination of resistance to water penetration -- Impact penetration test • ISO 18696:2006: Textiles -- Determination of resistance to water absorption -- Tumble-jar absorption test • ISO 9865:1991: Textiles -- Determination of water repellency of fabrics by the Bundesmann rain-shower test • ISO 9073-17:2008: Textiles -- Test methods for nonwovens -- Part 17: Determination of water penetration (spray impact) • ISO 4920:1981: Textiles -- Determination of resistance to surface wetting (spray test) of fabrics • AATCC Test Method 127-2008: Water Resistance: Hydrostatic Pressure Test • ISO 811:1981: Textile fabrics -- Determination of resistance to water penetration -- Hydrostatic pressure test • ISO 22958:2005: Textiles -- Water resistance -- Rain tests: exposure to a horizontal water spray. • AATCC Test Method 35, Water Resistance: Rain Test

	4. MMT	• AATCC Method 42, Water resistance: Impact penetration test -- • AATCC Test Method 195-2009 - Liquid Moisture Management Properties of Textile Fabrics
Colour Fastness tests	1.Light Fastness tester 2.Crockmeter (Colour Fastness to crocking) 3.Laundr-o-meter (Colour fastness to washing) 4.Glass plates, etc (Sea and chlorinated water fastness) 5. Perspirometer (Perspiration fastness) 6.Commercial Launderer (Domestic and commercial laundering fastness)	• ISO 105-B01:1994- Textiles -- Tests for colour fastness -- Part B01: Colour fastness to light: Daylight • ISO 105-B02:1994 -Textiles -- Tests for colour fastness -- Part B02: Colour fastness to artificial light: Xenon arc lamp fading test • ISO 105-B06:1998 - Textiles -- Tests for colour fastness -- Part B06: Colour fastness and ageing to artificial light at high temperatures: Xenon arc lamp fading test • AATCC 16-2004 -- • ISO 105-X12, • AATCC 8 & AATCC 165 -- • ISO 105- C 06 -- • AATCC 106:2007 & ISO 105-E02 :1996 (Colourfastness to Water: Sea) • AATCC 107:2007 & ISO 105-E01:1996 (Colourfastness to Water) • ISO 105 E03 & AATCC 162 (Chlorinated Water) -- • AATCC 15-2007 • ISO 105-E04:1996 -- • ISO 105- C06 /C08 • AATCC 61 No. 1A-5A
Oil Proof		AATCC 118

Table 2-1 Test methods and standards for assessing functional properties of textiles

C. Safety properties

This section reviews the tests applicable to human safety. Safety tests include, but are not limited to: 1. pH; 2. Formaldehyde; 3. Forbidden Azo-benzene colouring matter; 4. Flammability; 5. Non-toxicity; 6. Anti-static; 7. Heavy metals.

The different testing standards, testing equipment and methods used for human safety are listed in Table 2-2.

Test	Standards
pH	• ISO 3071:2005 - Textiles -- Determination of pH of aqueous extract • AATCC Test Method 81-2006 - pH of the Water-Extract from Wet Processed Textiles
Formaldehyde	• AATCC Test Method 112-2008 - Formaldehyde Release from Fabric, Determination of: Sealed Jar Method • ISO 14184-1:1998 - Textiles -- Determination of formaldehyde -- Part 1: Free and hydrolized formaldehyde (water extraction method) • ISO/DIS 14184-2 -Textiles -- Determination of formaldehyde -- Part 2: Released formaldehyde (vapour absorption method)
Forbidden Azo-benzene colouring matter	• BS EN 14362-1:2003 - Textiles. Methods for the determination of certain aromatic amines derived from azo colorants. Detection of the use of certain azo colorants accessible without extraction • BS EN 14362-2:2003 - Textiles. Methods for the determination of certain aromatic amines derived from azo colorants. Detection of the use of certain azo colorants accessible by extracting the fibres
Flammability	• 16 C.F.R. Part 1610—Standard For the Flammability of Clothing Textiles • ASTM D 6413 - Standard Test Method for Flame Resistance of Textiles (Vertical Test) • ASTM D1230 - Standard Test Method for Flammability of Apparel Textiles
Non toxicity	• OECD 201/202/203
Anti-static	• JIS L 1094
Heavy Metals	• EN 71 Part 3

Table 2-2 Test methods and standards for assessing the human safety of textiles

2.2.3. Ecological aspects

As discussed earlier, Eco-functional aspects include both environmental and functional considerations. The environmental aspect has received relatively little attention in terms of impact. Though the environmental (eco) impact aspect is a vast area, the following specific areas are emphasized in this study for the measurement of environmental impact of textiles: the 3Rs, biodegradability and minimal environmental impact.

1. The 3Rs

The 3Rs is the key to unresolved waste management issues and this concept assumes the top most priority in the waste management hierarchy (Li, 2007), as shown in Fig.2-1 (Information on Waste Hierarchy Options, 2009). The 3Rs refers to the following terms: Reduce, Reuse and Recycle. The waste management hierarchy can be traced back to the 1970s, when environment movements started to critique the practice of disposal-based waste management (Gertsakis and Lewis, 2003). These movements argued that 'rubbish' should not be perceived to be a homogenous mass that should be buried, instead they proposed that it was made up of different materials that should be treated differently, i.e. reused/recycled/composted/buried (Schall, 1992).

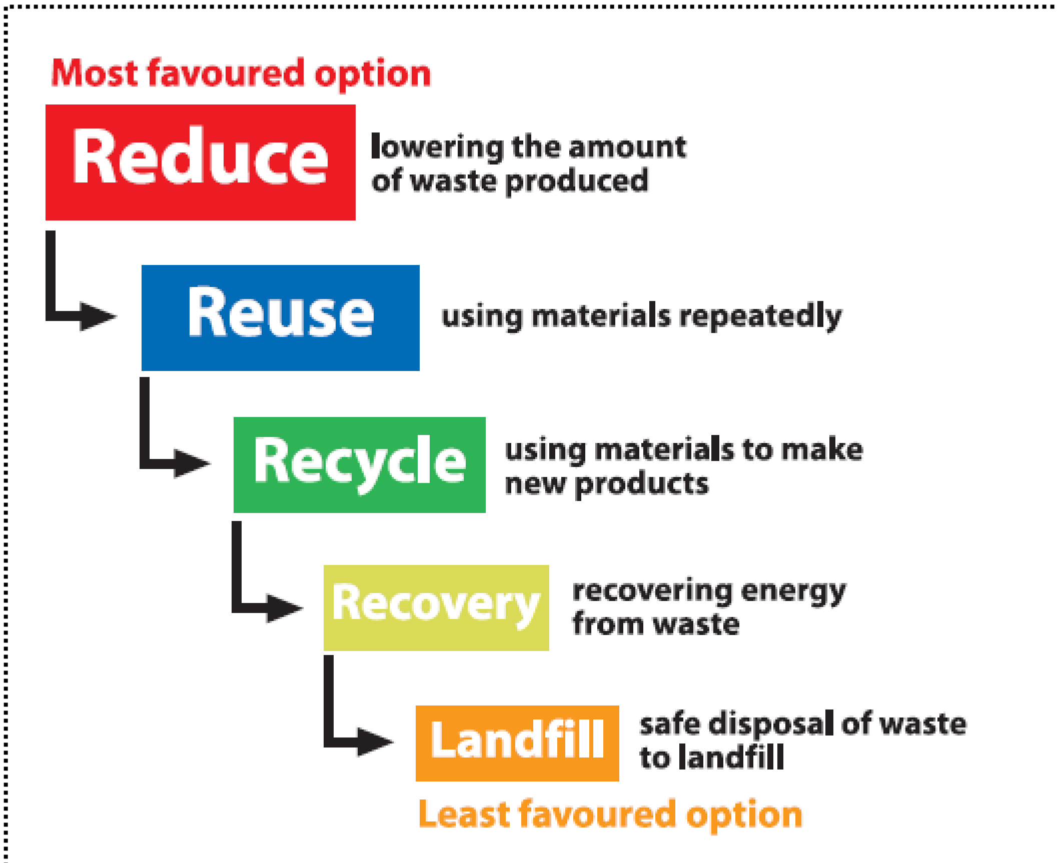


Figure 2-1 Waste Management Hierarchy (Information on Waste Hierarchy Options, 2009)

The waste hierarchy was first introduced into European Waste Policy in the European Union's Waste Framework Directive of 1975. In 1989 it was formalised into a hierarchy of management options in the European Commission's Community Strategy for Waste Management, and further endorsed in the commission's review of this strategy in 1996. Drawing on the precautionary principle, the waste hierarchy prioritised the prevention and reduction of waste, followed by reuse and recycling and lastly the optimisation of its final disposal. The concept is described as the "3Rs" - Reduce, Reuse, Recycle - followed by unavoidable disposal (The Waste Management Hierarchy, 2004).

The waste hierarchy has been applied almost exclusively to the field of post-consumer waste management. In reality, the waste hierarchy is an expression of the broader concept of the sustainable use of resources, exemplified by the 3Rs at the apex of the pyramid, as shown in Fig.2-2 (The Waste Management Hierarchy, 2004).

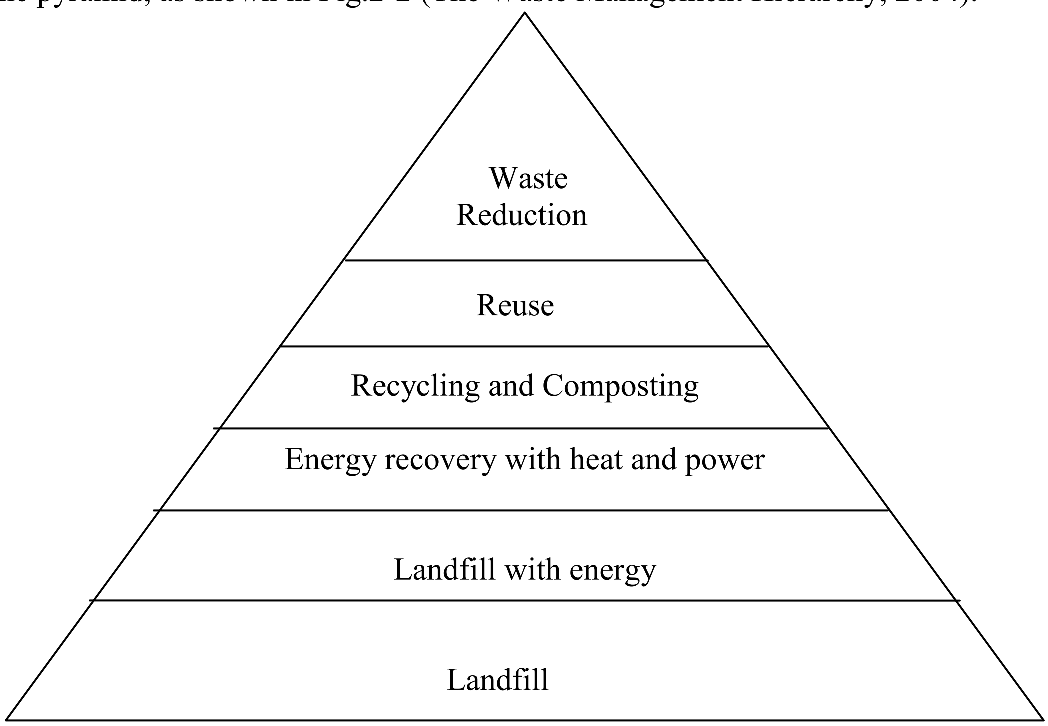


Figure 2-2 Waste Hierarchy Pyramid (The Waste Management Hierarchy, 2004)

The first R in the 3Rs refers to "Reduce" – reduction of waste in the production process itself. The idea behind this is that "an ounce of prevention is worth a pound of cure", i.e. it consumes less time and cost to tackle the causes of waste rather than treating them after production. It can be achieved by a combination of monitoring and analyzing the systems and processes of production (Waste Minimisation).

The second R refers to Reuse. The concept of reusability can be defined in two ways. The usual way is reuse of the product as a different one rather than discarding it as waste. For example, used plastic bags can be reused as liners/ supportive covers in dust bins. The second way of defining reusability is the usage of the particular product for the same purpose for which it was originally intended till it reaches its end of life or discarding stage. In simple terms, it is using the same product many times. Reuse is very imperative since it postpones the stage of discarding and it delays the start of a new product while the original product is still in the stage of being used. The first point also holds good as far as dumping in landfill sites in the early stages is concerned. Even, the second point deserves great appreciation since it is linked to the economy of an individual too, along with the benefits already discussed. Therefore, it is the responsibility of manufacturers to employ suitable raw materials and technology to manufacture any product to be reused many times and it is the liability of users to reuse the particular product many times till it can be discarded (Muthu et al., 2010a).

The last R refers to recycle. It refers to the conversion of old products discarded after use into new products. This process involves breaking down the old items and preparing new products. This helps in the diminution of wastage of materials which have the potential to be used again and trims down the consumption of fresh raw materials. It has other associated benefits such as reductions in cost, energy, pollution, etc.

Here the accountability lies with a government having the policies/provisions which make people motivated to opt for recycling of products rather than directly disposing of them to landfill. However, it is a fact that in addition to governmental policies, the keenness of people also matters greatly in the efficient recycling of products (Muthu et al., 2010a).

A simple description of environmental attributes and outcomes of the waste hierarchy is outlined in Table 2-3.

Goal	Attribute	Outcomes
Reduce	Preventative	Most desirable
Reuse	Predominantly ameliorative Part preventative	⇕
Recycle	Predominantly ameliorative Part preventative	
Treatment	Predominantly assimilative Partially ameliorative	
Disposal	Assimilative	Least desirable

Table 2-3 Environmental attributes and outcomes of the waste hierarchy (Gertsakis and Lewis, 2003)

The environmental, social and economic impacts and avoided impacts of different waste management options can be seen from Table 2-4.

Waste Management Option	Environmental impacts (-ve)	Avoided environmental impacts (+ve)	Social Impacts	Economic Impacts
Avoidance	None	Impacts at every stage of the product life cycle – materials, energy, emissions, wastes	Need to change consumption habits	Some products / components may not need to produced, with potential economic losses to manufacturers
Reduction	None	Impacts at every stage of the product life cycle – materials, energy, emissions, wastes	Cost saving to consumers	Cost saving to the manufacturer
Reuse	Transport – use of fuels, air emissions Cleaning –water, detergents	Impacts of materials processing and product manufacture – materials, energy, emissions, wastes Avoided landfill impacts – air emissions, leachate, visual impact	Need to change consumption habits	New business opportunities to establish collection & refurbishment service
Remanufacturing	Transport – use of fuels, air emissions Manufacture of	Impacts of materials processing and product manufacture – materials, energy, emissions, wastes	Need to change waste disposal patterns, i.e. source separation but does not encourage re-	New business opportunities in remanufacturing

	replacement parts – materials, energy, emissions, wastes Remanufacturing process - energy	Avoided landfill impacts – air emissions, leachate, visual impact	thinking about consumption habits	
Recycling	Transport – use of fuels, air emissions Reprocessing – energy, water, chemicals, emissions, wastes (Contamination, by-products)	Avoided impacts of manufacturing virgin materials - materials, energy, emissions, wastes Avoided landfill impacts – air emissions, leachate, visual impact	Need to change waste disposal patterns, i.e. source separation but does not encourage re-thinking of consumption habits	New business opportunities in reprocessing
Composting (organics)	Transport – use of fuels, air emissions Composting – energy, water, possibly odour	Avoided impacts of fertilizer and pesticide manufacture - materials, energy, emissions, wastes; water conservation and increased crop yield from use of compost as mulch; carbon sequestered in land	Need to change waste disposal patterns, i.e. source separation	New business opportunities in composting
Energy Recovery	Transport – use of fuels, air emissions Energy recovery process – energy, water, emissions, solid wastes (ash, grit,slag, scrubber residue)	Avoided impacts of energy production from other fuel sources – air emissions, waste water, solid wastes (ash) Avoided landfill impacts – air emissions, leachate, visual impact	Possible community opposition to new facilities – perception of environmental impacts Does not encourage re-thinking of consumption habits	New business opportunities in energy recovery
Treatment / stabilisation	Transport – use of fuels, air emissions Treatment process –materials, energy, wastes, possibly odour	Avoided landfill impacts – air emissions, leachate, visual impact; potential energy credit if anaerobic digestion is used (biogas collection and energy generation)	Possible community opposition to new facilities – perception of environmental impacts Does not encourage re-thinking of consumption habits	New business opportunities in waste treatment
Disposal – landfill	Transport – use of fuels, air emissions Landfill impacts – air emissions, leachate, visual impact	Avoided impacts of energy production from other fuel sources – air emissions, waste water, solid wastes (ash) due to gas recovery and energy generation; carbon sequestration	Community opposition to new landfills – visual / aesthetic impact	Low cost of disposal a disincentive to recovery and recycling

Table 2-4 Environmental, social and economic impacts and avoided impacts of different waste management options (Gertsakis and Lewis, 2003)

2. Biodegradability

The other important aspect of environmental impact is biodegradability. The term biodegradability is often confused with compostability. A material is defined as biodegradable if all of its organic components are subject to decomposition through biological activity. The term "compostable" refers to a material or mix of materials that can be decomposed in a composting system within one composting cycle (Biodegradability and Compostability). Biodegradability is the ability of a substance to be broken down into simpler structures by living organisms, thus reducing its life in the environment (Biodegradability). Biodegradability is a critical issue in the disposal of plastic waste. To tackle this, a great deal of research has focused on developing biodegradable plastics since 1990 (JoachimMller, 2004). The general mechanism of plastic biodegradation is shown in Fig.2-3.

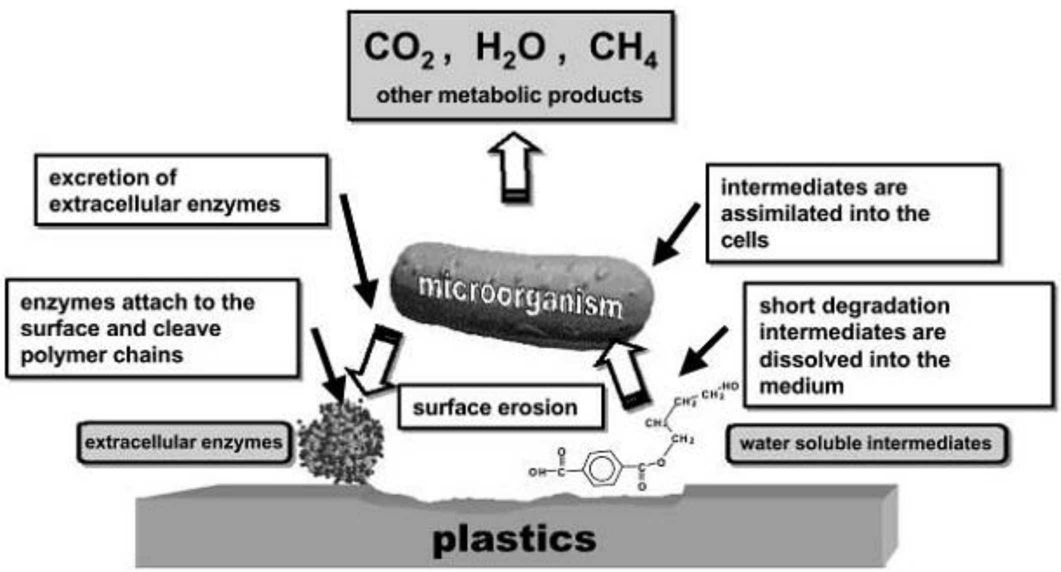


Figure 2-3 General mechanism of plastics biodegradation (JoachimMller, 2004)

When textiles are buried in soil, soil-resident microorganisms take part in the degradation of the textile materials, which is called biodegradation and biodegradability is often used as a standard measurement for the environmental friendliness of textile products (Park et al., 2004).

Evaluation of biodegradability

There are many methods and standards available to evaluate biodegradability. Some of these are:

1. ASTM D5338 - 98(2003) Standard Test Method for Determining Aerobic Biodegradation of Plastic Materials under Controlled Composting Conditions
2. ASTM D 5210 Standard Test Method for Determining the Anaerobic Biodegradation of Plastic Materials in the Presence of Municipal Sewage Sludge
3. ASTM D5511 - 02 Standard Test Method for Determining Anaerobic Biodegradation of Plastic Materials under High-Solids Anaerobic-Digestion Conditions
4. ASTM D5526 - 94(2002) Standard Test Method for Determining Anaerobic Biodegradation of Plastic Materials under Accelerated Landfill Conditions
5. ISO 14855-1:2005 - Determination of the ultimate aerobic biodegradability of plastic materials under controlled composting conditions -- Method by analysis of evolved carbon dioxide -- Part 1: General method
6. ISO 14855-2:2007 - Determination of the ultimate aerobic biodegradability of plastic materials under controlled composting conditions -- Method by analysis of evolved carbon dioxide -- Part 2: Gravimetric measurement of carbon dioxide evolved in a laboratory-scale test
7. ISO 14852:1999 -Determination of the ultimate aerobic biodegradability of plastic materials in an aqueous medium -- Method by analysis of evolved carbon dioxide
8. ISO 15985:2004 - Plastics -- Determination of the ultimate anaerobic biodegradation and disintegration under high-solids anaerobic-digestion conditions -- Method by analysis of released biogas.
9. AATCC 30:2004 – Soil burial test

3. Minimal environmental impact

Any product of process or service is expected to cause minimal impact to the environment. The process of measuring the impact of different products/processes/services on the environment is called "Environmental Systems Analysis". In a description of the course 'Applied Environmental Systems Analysis', it is stated that 'Environmental Systems Analysis treats analysis and assessment of the interaction between anthropogenic (human-made) systems and their environment(s). It aims at providing a basis for decisions and planning for a more sustainable behaviour at an individual, organizational and societal level' (KTH). The Environmental Systems Analysis group at Wageningen University in the Netherlands describes it as 'a quantitative and multidisciplinary research field aimed at combining, interpreting and communicating knowledge from the natural and social sciences and technology' (Wageningen University). At Chalmers University of Technology, the research department of Environmental Systems Analysis describes ESA as 'including methods and tools for the environmental assessment of technical systems of different kinds' (Chalmers University of Technology).

The term ESA tool is used in the present study to describe methods and tools for the environmental assessment of human-made systems using a systems perspective. Environmental information gained by using ESA tools can be used for learning purposes or communication, or to facilitate more informed decision-making. Some of the ESA tools studied also consider other aspects, economic and/or social (Moberg, 2006).

A large number of tools are available for measuring environmental impact (Baumann and Cowell, 1999; Dale and English, 1999; Miljöverktyg, 2000; Petts, 1999; SETAC, 1997; Wrisberg et al., 2002). These tools can be divided into procedural and analytical types (Wrisberg et al., 2002). According to Finnveden and Moberg, procedural and analytical tools for ESA include: Environmental Impact Assessment

(EIA), System of Economic and Environmental Accounting (SEEA), Environmental Auditing, Life-Cycle Assessment (LCA) and Material Flow Analysis (MFA) (Finnveden and Moberg, 2005).

EIA (Environmental Impact Assessment) is a procedural tool mainly for assessing environmental impacts of projects (Petts, 1999) and it is required by law in some situations. This tool describes the environmental impact of a suggested project and its alternatives (e.g. the construction and localisation of a waste incineration plant). How the assessment of environmental impact should be made is not predefined and analytical ESA tools can be used within EIA (Moberg, 2006).

The SEEA is a system of satellite accounts to the system of national accounts. It has economic activities within a nation as its primary object. It includes both systems for physical accounts, i.e. measures of inputs and outputs (resources used and emissions) and monetary accounts (Finnveden and Moberg, 2005).

Environmental Auditing is mainly a procedural tool applied on an organisation, for example, a company or a governmental agency. Environmental Auditing is a descriptive assessment typically including environmental aspects as well as resource use (Finnveden and Moberg, 2005).

Life-Cycle Assessment (LCA) is an analytical tool used to evaluate the environmental impacts of a product throughout its life cycle. The term ‘product’ can include not only product systems but also service systems (Finnveden and Moberg, 2005). A series of ISO standards have been developed for LCA providing a framework, terminology and some methodological choices (ISO 14040, 2006; ISO 14044, 2006; ISO 14047, 2003). Initiatives have also been taken to develop best available practice (Udo de Haes et al., 1999; Udo de Haes et al., 2002). Further details about LCA are explained in detail in section 2.2.5.

Material Flow Analysis (MFA) is also an analytical tool that focuses on material flows, especially on the input side. Different MFA methods have different objects of focus. Some of the MFA methods include: Total Material Requirement (TMR), Material Intensity per Unit Service (MIPS) and Substance Flow Analysis (SFA) (Finnveden and Moberg, 2005). MFA is a systematic approach aiming at presenting an overview of the materials used in a company, identifying the point of origin, the volumes as well as the causes of waste and emissions, creating a basis for an evaluation and forecast of future developments and defining strategies to improve the overall situation (Information on Material Flow Analysis).

The other tools include: Ecological Footprint (EF), Energy Analysis (En), Risk Assessment (RA), etc, which are not reviewed. A comparative view of different tools is shown in Fig.2-4, in which the tools are shown in relation to their focus, i.e. the object to which the impacts are related and to which aspects are included in the study. The procedural tools are written in bold text.

2.2.4. Impact of textile processes on environment and human

An environmental analysis of textile manufacturing with regards to textile fibres (Chen and Burns, 2006) can be seen in Table 2-5, which lists the environmental analysis of textile fibres in terms of different factors such as whether they are nonpolluting to obtain, process and fabricate, made from renewable or non-renewable resources, fully biodegradable or not, reusable or recyclable.

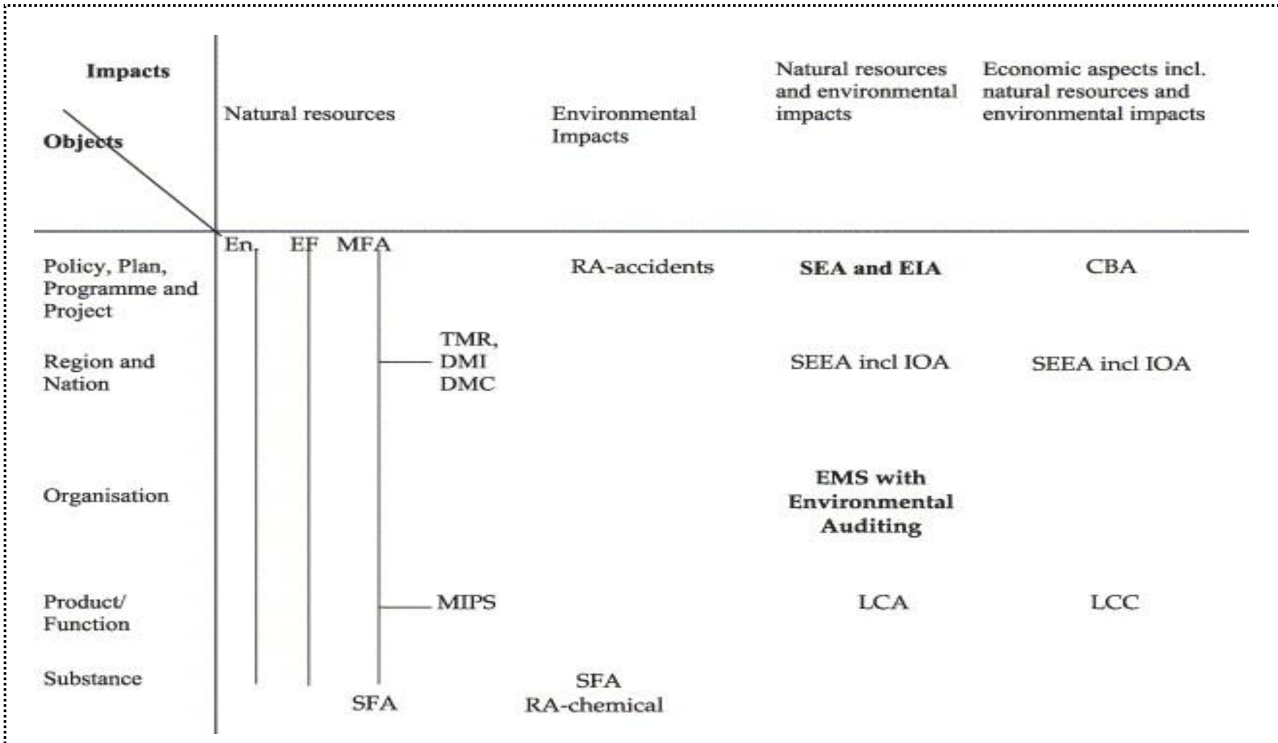


Figure 2-4 A comparative view of various environmental assessment tools (Finnveden and Moberg, 2005)

Textile Product	Nonpolluting to obtain, Process, and Fabricate	Made From Renewable resources	Fully Bio degradable	Reusable/ Recyclable
Cotton*	No Fertilizers, herbicides, pesticides, dyes and chemicals used can pollute air, water and soil	Yes Cotton Comes from cotton plants that are renewable	Yes	Yes But it is difficult to recycle cotton from postconsumer products because of the presence of dyes and other fibers
Wool*	No Runoff contamination, Chemicals used for cleaning, dyeing, and finishing can cause pollution	Yes Wool comes from sheep, which are renewable	Yes	Yes It can be recycled
Rayon*	No Harsh Chemicals used to process wood pulp and dyes and finishing chemicals can cause pollution	No Wood pulp used for rayon comes from mature forest	Yes	Yes But Rayon fibres have not been recycled
Tencel*	No Chemicals used for dyeing and finishing can cause pollution	Yes Trees used for Tencel are replanted	Yes	Yes But Tencel has not been recycled
Polyester*	No Chemicals used for dyeing and finishing can cause pollute air & water	No Petroleum resources are not renewable	No	Yes 100% PET has been recycled

Nylon*	No Chemicals used for dyeing and finishing can cause pollute air & water	No Petroleum resources are not renewable	No	Yes 100% Nylon has been recycled
Olefins	No Chemicals used for dyeing and finishing can cause pollute air & water	No Petroleum resources are not renewable	No	Yes 100% PP/PE has been recycled

Table 2-5 Environmental analysis of textile fibres (Chen and Burns, 2006)

Further to the analysis of fibres, Tables 2-6 to 2-11 summarize the environmental and health impacts of the different textile processes from spinning to garment manufacturing processes (Environmental and Health Impacts of different textile processes). Tables 2-6 and 2-7 explain the different chemicals used, impacts of gaseous emissions, effluents and solid wastes in spinning (cotton and wool) and fabric formation processes.

Process	Chemicals used	Impact of gaseous emissions	Impact of effluents	Impact of solid wastes
Cotton Spinning				
Opening	Cotton dust ,soil, particulates, bacteria, fungi, pesticides	Byssinosis (brown lung) disease, risk of chronic bronchitis	_____	_____
Spinning	_____	_____	_____	_____
Wool spinning				
Scouring	Detergents, Sodium sulphate, soaps, alkalis, Sulfuric acid (for grease recovery)	Volatile Organic Compounds (VOC) (solvents) may cause bloating, diarrhoea. Irritant to eyes and skin. Cationic detergent is more toxic	High biological oxygen demand (BOD), high pH disturbance of aquatic life. Not readily degradable, chemical oxygen demand (COD)	Sludge containing toxic substances
Carbonizing	Sulfuric acid , Sodium carbonate (for neutralization)	Acid fumes cause irritation of the eyes, nose and throat	Occasional acid bath dumps, stains the skin brown to yellow.	Charred carbon residue, which affects respiratory system
Spinning	Noise (causes hearing problems)	Particulates	_______	________

Table 2-6 Health and environmental impacts in the spinning industry (Environmental and health impacts of different textile processes)

Process	Chemicals used	Impact of gaseous emissions	Impact of effluents	Impact of solid wastes
Sizing	Natural starch, polyvinyl	VOCs, methanol from PVA, is	Washing residues cause	______

	alcohol, carboxymethyl cellulose, oils, waxe s, adhesives Urea, diethylene glycol, etc.	toxic at high levels, causing central nervous system damage and blindness Higly flammable, forms air pollutants	high BOD and COD, metals (from size additives) causing disturbance of aquatic life	
Weaving	Noise causes hearing disabling, particulates	Particulates cause respiration and hearing problems	________	_______
Knitting	Particulates, noise, but less than weaving, not causing much problems in hearing	Particulates affect health	________	_______
Nonwoven	Chemical adhesive and particulates	VOCs, cause respiratory troubles	________	_______
Tufted	Resin coating causing formaldehyde	Formaldehyde kills tissues, intense irritation of eyes and nose and headaches carcinogenic.	________	_______

Table 2-7 Health and environmental impacts in the fabric formation industry (Environmental and health impacts of different textile processes)

With respect to nonwovens, the glue being used in the manufacturing process of nonwovens can be responsible for emission of toxic liquids which may cause water pollution, in particular may poison aqueous species (Slater, 2003). Tables 2-8 and 2-9 discuss the different chemicals used, impacts of gaseous emissions, effluents and solid wastes in the different processes that constitute the finishing and garment manufacturing industries.

Process	Chemicals used	Impact of gaseous emissions	Impact of effluents	Impact of solid wastes
Singeing	Small amounts of exhaust gases, negligible impact	________	________	________
Desizing	- Enzymes or Sulfuric Acid for starch, detergents and alkali for poly vinly alcohol and Carboxymethyl cellulose (CMC)	May cause bloating and diarrhoea. Irritant to eyes and skin	High BOD or COD, high temperature, size impurities, lubricants, metals.	Residues of solvents
Scouring	Sodium hydroxide, Sodium carbonate, Surfactants, chlorinated solvents	Non-ionic detergents may cause bloating and Diarrhoea, Irritant to eyes and skin.	High BOD and temperature, very high pH, fats, waxes, size residues, causing disturbance of	________

			aquatic life	
Bleaching	-Hypochlorite -Hydrogen -peroxide -Acetic acid	Chlorine gas released, causing severe irritation of respiratory tract and eyes tract and eyes Toxic gases	Low to moderate BOD, high pH and temperature	________
Mercerization	Sodium hydroxide, surfactants, acid, liquid ammonium	________	Very high pH and dissolved solids, some BOD	________
Dyeing	- Dyestuffs - Auxiliaries - Reductants - Oxidants - Dye dust is a main source of pollution for breathing or skin	- Ammonia is irritating to the skin, eyes nose, throat, and upper respiratory system. Basic dye is generally toxic (e.g. crystal violet) - Potassium dichromate can cause dermatitis and ulceration, it is carcinogenic - Exposure to dye dust through breathing or skin can result asthma, eczema, and severe allergic reactions.	- Heavy metals e.g. (Cu,Cr) - Carcinogenic amines - Toxic compounds, e.g. carriers - Hydrogen sulfide - Corrosion, - Irritant - For wool dye, high BOD, possibly toxic, and pH low	Chemical residues can cause allergic reactions to skin or respiratory system.
Printing	-Dyes(acids or alkalis), pigments, kerosene, binders, other additives - Ammonia - Xylenes	- Formaldehyde causes intense irritation of eyes and nose, and headaches. It is carcinogenic - Kerosene causes nausea, vomiting coughing, leading to respiratory paralysis - Ammonia vapour is severe irritant to eyes, causes vomiting, diarrhoea, sweating and coughing. High concentration can cause respiratory arrest.	- Heavy metals (toxic) - Carcinogenic - Irritants - Fire hazard - High BOD& COD depending on type of thickener - Disturbance of aquatic life, eg. urea and phosphate	Chemical residues can be irritant and toxic.
Chemical finishing: - Anticrease - Flame proofing - Softening	- Formaldehyde - Phosphorus - Softeners - Fluorinated chemicals - Catalyst s - Formaldehyde - Ammonia	Intense irritation of eyes and nose and headaches. Carcinogenic. Causing vomiting, and coughing. High concentration can cause respiratory arrest.	- BOD and COD - Carcinogenic - Skin allergies - Heavy metal toxicity	Chemical residues can be hazardous and toxic
Water-proofing	- Paraffin - Aluminium salts - Zircon salts - Silicone - fluorocarbon resins	Toluene may be used in solvent coating operations can cause, headaches, confusion weakness, and memory loss, and affects function of kidney and liver , formation of ozone which causes asthma	Fluorocarbon resins may cause disposal problems BOD,COD	Chemical residues may contain hazardous chemicals.
Antistatic finishing	Surface- active substances	Possibly skin allergies	BOD,COD, additive residues	Resin residues may be skin allergy

Anti-felt finish (for wool)	- Chlorine - Polyamide - Epich chlorohydrin resin	Chlorine vapour is hazardous, and can cause respiration problems	Large quantities of effluent with COD	________
Moth and beetle protection (for wool)	- Chlorinated sulphonamide derivatives - Biphenyl ether - Urea derivatives - Pyrethroids	Pyrethroids may cause neuro toxic effects	COD	Chemical residues may be hazardous
Weighting	- Stannic chloride - Sodium phosphate - Water glass	VOCs, combustion exhausts have effect on skin	Large quantities of effluent with COD	Chemical residues may be hazardous
Hydrophilising	- Polyamide - Polyacrylic - Silicon	VOCs, possibly skin allergies	Large quantities of effluent with COD	Chemical residues may be hazardous
Delustering	- Phenol - Turpentine - Pine oil - Glauber salt - Barium chloride - Resins containing formaldehyde - Alkali sulphide	- Allergy inducing - In some cases carcinogenic substances	COD, heavy metals	Chemical residues may be hazardous
Abrasion resistant finish	- Silica gel - Plastic resins	VOCs, causing irritation of respiratory system. Skin allergies	Large quantities of effluent with COD, toxicity	Chemical residues may be hazardous
Sanforizing	- Urea formaldehyde - Melamine formaldehyde	- Skin allergies - Carcinogenic properties	- Wastewater, BOD - Toxicity,	Resin residues may be carcinogenic

Table 2-8 Health and environmental impacts in the finishing industry (Environmental and health impacts of different textile processes)

Process	**Chemicals used**	**Impact of gaseous emissions**	**Impact of effluents**	**Impact of solid wastes**
Cutting fabrics	No chemicals Particulates	Little effect on respiratory system	________	________
Fusing the interlining to fabric pieces	Fumes of interlining adhesive resin, and fabric finish	Slight effect of adhesive fumes on respiratory system (VOCs)	________	________
Sewing	Particulates	Negligible effect on respiratory system	________	________
Ironing	Fumes from fabric	Negligible effect on respiratory system	________	________

Table 2-9 Health and environmental impact in the garment industry (Environmental and health impacts of different textile processes)

Tables 2-10 and 2-11 list the different chemicals used, impacts of gaseous emissions, effluents and solid wastes in man-made fibre manufacturing processes and service units.

Process	Chemicals used	Impact of gaseous emissions	Impact of effluents	Impact of solid wastes
Viscose Rayon				
Soaking in caustic soda	Caustic soda solution	Vapour of caustic soda causes some allergies	________	________
Xanthating	Carbon disulphide	Vapour of carbon disulphide and Hydrogen sulphide may affect respiratory system	________	________
Spinning	Sulpheric acid, sodium sulphate, zinc sulphate	Vapour of acid and chemicals irritate respiratory system	________	Yarn scrap with acid and chemical may be hazardous
Scouring and finishing	Sodium sulphide	Vapour of acid, and chemicals may affect respiratory system	Wastewater containing acids, low pH and organic substances	________
Nylon				
Polymerization	Caprolactum, acetic acid	Exposure to acetic acid gas or spray can cause intense irritation of the eyes, nose, throat and skin damage	________	________
Spinning	Finishing oils, mineral oils, Nitrogen gas. Noise	Negligable effect on health. Nitrogen may have an effect. Noise may affect hearing	Wastewater containing oils, reducing the dissolved oxygen	________
Texturing	- Low molecular fractions of polymer - Spin finishes - Additives	Exhaust air may be hazardous to respiratory system	Wastewater containing finishing chemicals and additives	________
Polyester				
Polymerization	- Cobalt 60, for level control of cotton type polyester - Cesium 137 for level control of wool-type polyester - Methanol results from easter- exchange reactor	- Level of radiation may have serious effect. - Volatilised monomers and additives - Methanol is toxic to humans. At high dose levels causes central nervous system damage and blindness.	________	________
Spinning	________	________	________	________
Tensioning	Finishing olis, and water	________	Wastewater containing chemicals, reducing the dissolved oxygen	________

Table 2-10 Health and environmental impacts in man-made fibre manufacturing (Environmental and health impacts of different textile processes)

Process	Chemicals used	Impact of gaseous emissions	Impact of effluents	Impact of solid wastes
Transportation	- Vehicle exhausts, gasoline fumes	Gasoline fumes cause irritation of respiratory system	Oils reduce dissolved oxygen	_____
Boilers and steam system	- Naphtha, coal, natural gas, oil fuel	Particulates, burning exhausts, cause irritation of respiratory system	Wastewater with precipitated salts reduces the dissolved oxygen	_____
Water treatment	- H2So4 / Hcl and NaOH (for ion exchange) - NaCl (water softening), trisodium phosphate (boiler water), chlorine or hypochlorite (for water disinfiction)	_____	_____	Chemical residues may be allergic.
Wastewater treatment.	- Alum or ferric salts, flocculant polymers, H2SO4 / HCl and NaOH / CaO, - Nutrients (urea, phosphoric acid, ammonium phosphate)	VOCs from fabric chemicals, vapours and mists, may cause, irritation of respiratory system	_____	Wastewater sludge may cause skin irritation

Table 2-11 Health and environmental impacts in service units (Environmental and health impacts of different textile processes)

2.2.5. Life cycle assessment

A life-cycle assessment (LCA) is an analytical tool which helps us to understand the environmental impacts from the acquisition of raw materials to final disposal (SETAC, 1993). According to the definition given by The Society of Environmental Toxicology and Chemistry (SETAC), LCA is an iterative process used to evaluate the environmental burdens associated with a product, process or activity by identifying and quantifying energy and materials used and waste released to the environment; to assess the impact of the energy and material uses and releases to the environment; and to identify and evaluate opportunities to effect environmental improvements. The assessment includes the entire life cycle of the product, process or activity, encompassing extracting and processing raw materials; manufacturing, transportation and distribution; use, reuse, maintenance, recycling and final disposal (Fava et al., 1991).

According to ISO 14040 and ISO 14044, an LCA study essentially consists of four interconnected steps (ISO 14040, 2006; ISO 14044, 2006) (see Figure 2-5):

- Goal and scope definition
- Inventory analysis
- Impact Assessment
- Interpretation

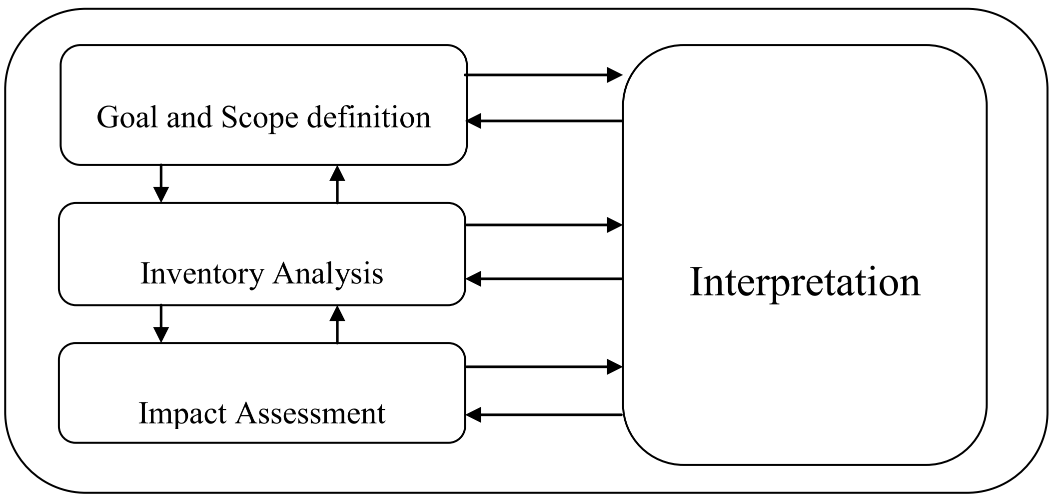


Figure 2-5 Phases of LCA

In the first step (goal and scope definition), the term goal is used to specify the application of study, to state the very purpose of pursuing the study and also to identify the target audience. The definition of scope aims at prescribing the breadth, the depth and the complete details of the study. It is vital to define a functional unit, which is an object of the life cycle assessment study and the boundaries of the system under investigation with clear specifications of data quality requirements. This step and the following step of inventory analysis correspond to ISO 14040 and ISO 14044 (ISO 14040, 2006; ISO 14044, 2006).

The second step – Inventory Analysis, (LCI – Life cycle Inventory) focuses on analyzing the different flows of material and energy corresponding to the production of the product and the environment. The data pertaining to the flows of input and output are collected in this phase (ISO 14040, 2006; ISO 14044, 2006), as shown in Fig.2-6. Input flows refer to the various resources like raw materials, energy or land or indeed any factor in the production of the product. Output flows mean any sort of emissions to air, water or to land.

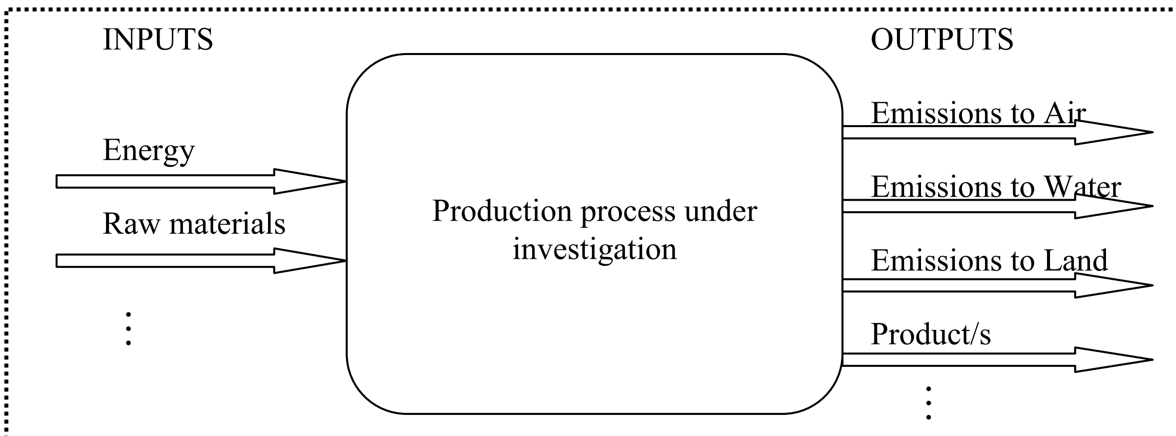


Figure 2-6 Data to be collected in LCI

The next step - Impact Assessment (LCIA -Life Cycle Impact Assessment), deals with the exploration of the implication of impacts made on the environment derived from the outcome of the inventory analysis. In other words, in this phase, the results of the inventory analysis step are interpreted in terms of the environmental impacts. Various effects deduced in this step can be compared to arrive at the overall assessment of the products under investigation. In the impact assessment phase, LCIA consists of both obligatory and optional elements in accordance with ISO 14040. The elements are represented diagrammatically in Fig.2-7.

In brief, this step consists of selection and definition of impact categories such as Global Warming, Acidification, Eutrophication, Human Toxicity, Ozone depletion, Photo-oxidant formation, Depletion of abiotic resources and Aquatic and terrestrial toxicity measures, etc and classifies them by assigning the results from the Impact Assessment to the relevant impact categories. A common unit is defined for each category by aggregating the inventory results in terms of adequate factors called as, “Characterization factors” of different types of substances within the impact categories (Sonnemann et al, 2003).

The final step is Interpretation of LCA, which is in accordance to ISO 14040 and ISO 14044 (ISO 14040, 2006; ISO 14044, 2006), and aims primarily at drawing conclusions from the study and also making suitable recommendations to eliminate major impacts encountered, if any. The entire process of the life cycle assessment is iterative (Guinee et al., 2002).

There are many variants of life cycle assessment depending on the stage of assessment and these are explained below (Information about Life Cycle Assessment):

1. Cradle to Gate: Partial life cycle study, where study of impacts is confined till the production stage of the product (before being sent to customer);

2. Cradle to Grave: Complete or full life cycle study, where study of impacts is extended up to the end-of-life disposal state;

3. Cradle to Cradle: An explicit category of cradle-to-grave assessment, where the end-of-life disposal state is a recycling process whereby identical or new products are created again.

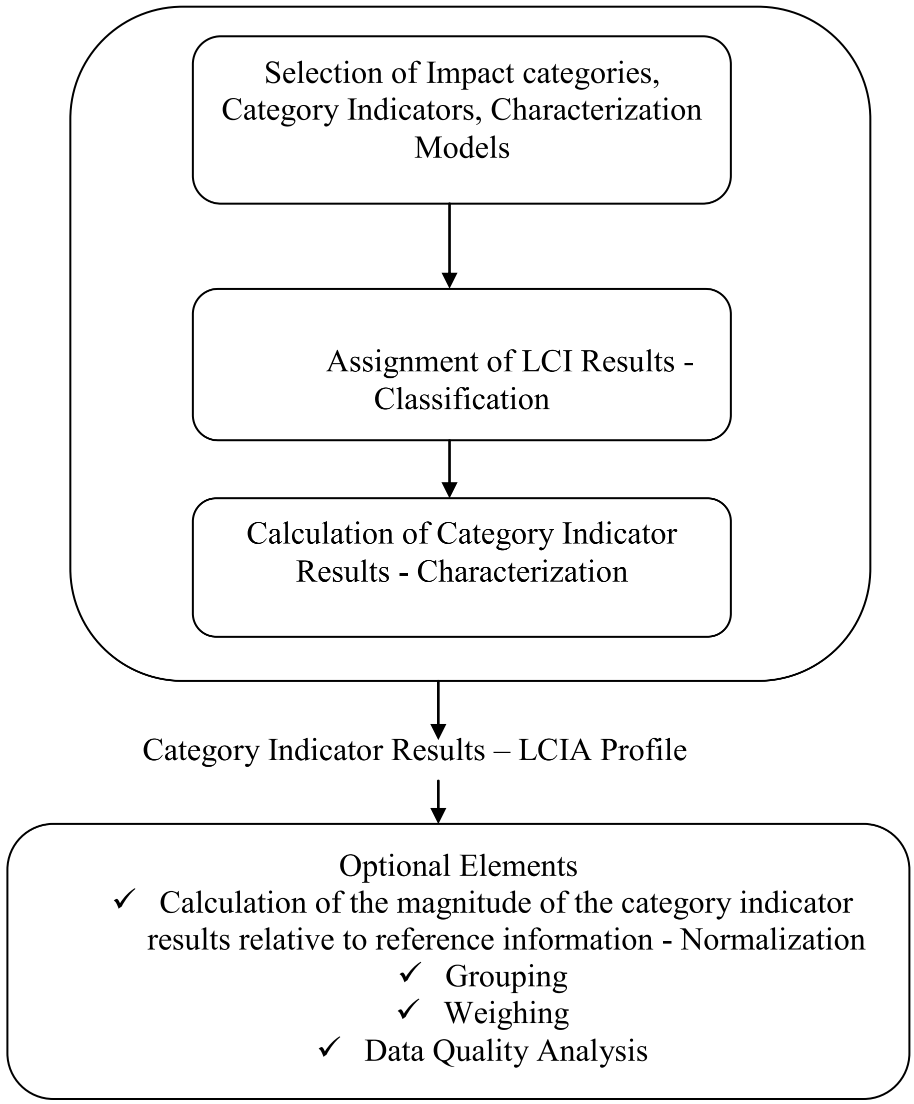


Figure 2-7 Obligatory and optional elements of LCIA

2.2.6. Sustainable development and environmental assessment of textiles

The concept of sustainability is not new and can be defined in numerous ways. A famous and appropriate definition given by the World Commission on Environment and Development is, "Development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Bruntland, 1987). The concept of sustainability is being practised in most of the fields and it is a common theme across the globe. In a more specific sense, sustainability is the concept of using the renewable or replenishable resources; so that we do not exhaust all our existing resources and so let the next generation suffer (Bruntland, 1987).

The same concept, when applied to textiles, can be defined as textile products produced using raw materials, energy and other ingredients which are derived from renewable resources that cannot be exhausted and consequently do not affect the next generation. Similarly a sustainable fibre is one which is manufactured/produced using raw materials and energy which is derived entirely from renewable resources (Bruntland, 1987).There has been tremendous confusion prevailing over the sustainability impacts of producing textile materials. Synthetic fibres are commonly seen as 'bad' and natural fibres as 'good' (Fletcher, 2008).

Sustainability has many faces and facets, one among them is ecological sustainability and this is very closely linked to environmental protection. Environmental protection and sustainable development have been gaining more public attention and political importance in recent years. Assessment of textile products in terms of their environmental consequences by means of a simple life cycle analytical model was dealt with by Horrocks, et al (Horrocks et al., 1997). This paper dealt with the assessment of flame retardant textiles from the fibre stage to the disposal stage but uses subjective rankings without complete empirical data. Although the study considers all aspects of textiles in terms of life cycle, there is still a dearth of information about the objective assessment of different fibres. Surprisingly, very little research has been carried out to assess the currently available fibres in terms of their ecological sustainability and particularly by considering the ecological benefits gained by the fibres due to photosynthesis, which is an interesting and unexplored part in the field of ecological assessment of textile fibres. Even though currently available life cycle models address numerous issues, some major issues such as the recyclability, biodegradability, inclusion of positive effects of plants and trees to off-set global warming, etc have not been given due consideration. Hence there is a need to develop a comprehensive model which can include all these factors to determine the ecological sustainability of various textile fibres.

2.3. Shopping bags

Shopping bags are considered as the base material in this research work for evaluation of their eco-functional properties. Hence this section reviews the literature concerning the different types, production processes and life cycle assessment studies carried out on shopping bags and also the test methods applicable to shopping bags. It is more appropriate to discuss shopping bags in the context of packaging, though they can be discussed in other contexts as well such as branding and marketing communications (Prendergast et al., 2001).

The term “shopping bag” can be used interchangeably with the terms “package” and “packaging”. According to Kotler and Armstrong (1996), a package’s primary function, traditionally, is to contain and protect the product, which is what a shopping bag does. According to the European Community (EC), packaging refers to “all products made of any materials of any nature to be used for the containment, protection, handling, delivery and presentation of goods, from raw materials to processed goods, from the producer to the user or the consumer” (Prendergast et al., 2001). Shopping bags, as a package, serve the utilitarian purpose of providing transportation and protection for merchandise bought in retail establishments of all kinds (Mullin, 1995). They can also be regarded as a form of promotion, a status symbol, a collective and a work of art (Mullin, 1995; Sayles, 1996).

2.3.1. Types of shopping bags

Based on the technology of manufacture and raw materials utilised, four major varieties of shopping bags dominate in the market today. They are plastic bags, paper bags, nonwoven bags and woven bags (Muthu et al., 2010b). A plentiful array of raw materials, styles, designs are being employed to manufacture them, which makes for numerous sub types of shopping bags (Muthu et al., 2010a).

2.3.2. Production processes

Plastic bags

Plastic bags are made from non-renewable resources, where the key ingredients are petroleum and natural gas. Polyethylene - High Density (HDPE), Low Density (LDPE), linear low-density polyethylene (LLDPE) are the raw materials widely used for the manufacture of plastic bags (Lajeunesse, 2004). The shopping bags used by supermarkets would be ideally produced from LLDPE to achieve the desired thickness and glossy look. If one needs very thin and filmy bags, LDPE is an ideal choice (Ellis et al., 2005). The oil used for manufacturing plastic bags accounts for 4% of the world's total oil production (www.greenfeet.net; www.angelfire.com). The production outline of plastic bags in general is shown in Fig.2-8, which depicts a generalised picture of the manufacture of plastic products and plastic shopping bags (Plastic Shopping Bag

Making). The shape and structure of plastic bags enable users to carry them easily and they are found to be cheaper in cost compared to paper bags. Also, they have the capacity to be reused and recycled. Such recycling activities can be found in supermarkets and one can see many slogans in this respect in supermarkets in most countries. Their rate of decomposition, however, is low and can be as long as 1000 years (Stevens, 2001)and most of the plastic bags, say up to 96%, are thrown into landfills (Williamson, 2003).

Paper bags

Paper bags are made out of pulpwood from trees, which is a renewable source. However, paper bags are obtained by destroying trees, which harms both plants and animals and is produced by energy created by burning coal or natural gas. The pulp created in the paper making process will be converted into paper bags by different processes and machines after consuming tremendous amounts of energy from fossil fuels and electricity and treatment by various chemicals, etc. (www.angelfire.com). An outline of the manufacturing process of paper shopping bags is given in Fig.2-9. However, papers bags are biodegradable and can be recycled to create corrugated cardboards.

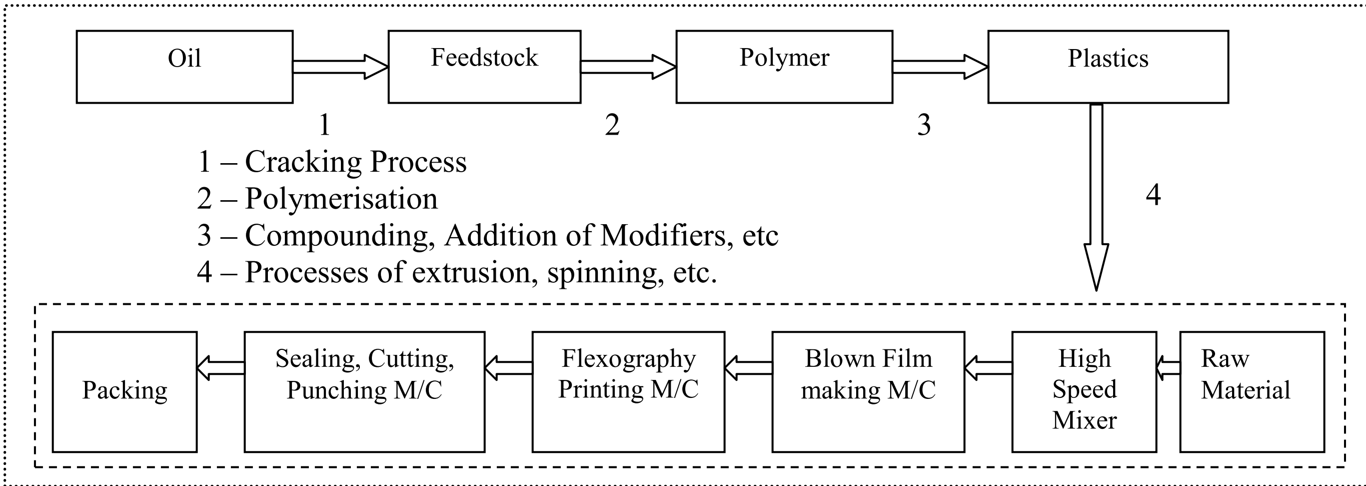


Figure 2-8 General outline of the plastic bag manufacturing process

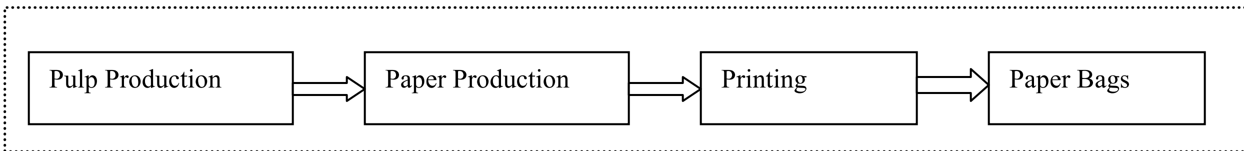


Figure 2-9 Process outline of paper shopping bag manufacture

Nonwoven Bags

Though nonwoven bags made from different raw materials are available today in the market, those made of Polypropylene (PP) are common for shopping purposes. Hence nonwoven bags made of PP are chosen for this study. PP is derived from non-renewable resources, the key ingredients of which are petroleum and natural gas. PP is manufactured by the process of polymerization of propylene, which is a gaseous by-product obtained during petroleum refining. This action takes place in the presence of a catalyst under carefully-controlled heat and pressure (Maier and Calafut, 1998). PP manufactured in chips form is used as a raw material for the spunbonding process, which is a one-step process for manufacturing nonwoven fabric from plastic resin (Maier and Calafut, 1998). Spunbonding is a commercially available polymer-laid process (Bhat and Malkan, 2007). The fundamental stages of this process include polymer melting, filtering and extrusion, quenching, drawing, laying down on a forming screen followed by bonding and finally roll-up (Bhat and Malkan, 2007). These stages are then followed by processes of cutting, screen printing and sewing. An outline of the production process of nonwoven bags is given in Fig.2-10.

Woven Bags

The production process of a woven bag is cumbersome compared to a nonwoven bag. This paper focuses on woven cotton bags (calico). The manufacturing sequence starts from the growing of cotton (either conventional or organic cotton), followed by the separation of cotton fibres from seed cotton, followed by spinning, weaving and colouration processes. These are followed by the regular processes of cutting, screen printing and sewing. An outline of the production process of woven bags is given in Fig.2-11.

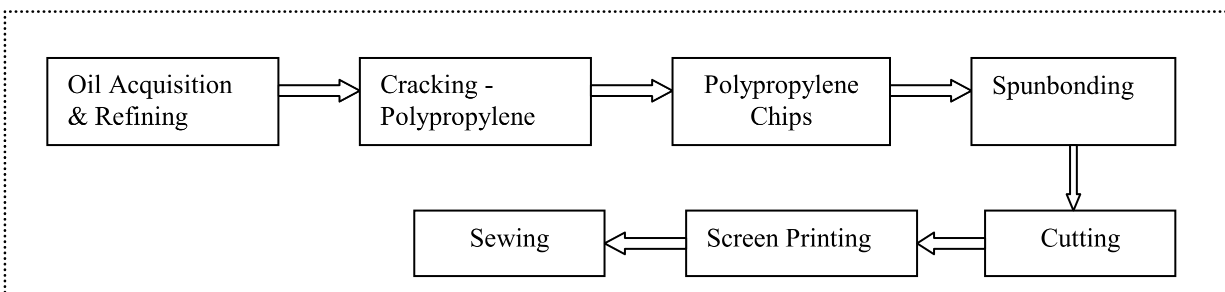


Figure 2-10 Manufacturing process of nonwoven bags

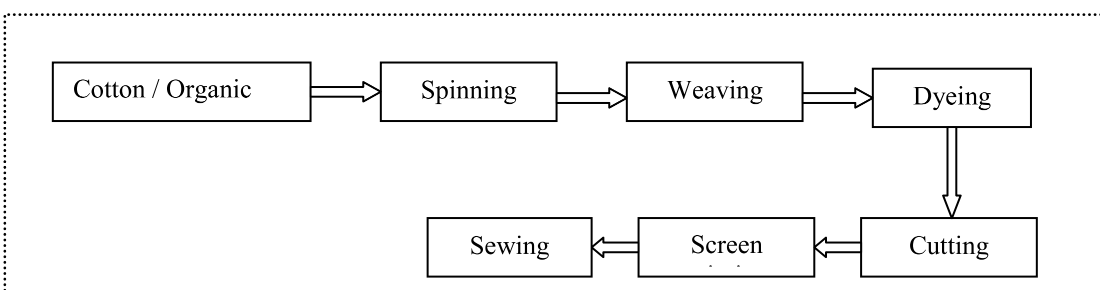


Figure 2-11 Manufacturing process of woven bags

2.3.3. LCA of shopping bags

Any product will have an impact on the planet and quantifying the impact is crucial to reduce it. Among many techniques to study the eco-impact of a product, life cycle assessment (LCA) is one of the most widely used and popular ones. LCA examines the product from its initial stage (cradle stage) to final stage (grave stage), covers its entire life cycle, and also evaluates the product in terms of eco-impact during its life time.

Shopping bags, being perceived as a symbol of throw-away society, demand LCA to assess their eco-impacts. There has been a dearth of research articles published on the subject of shopping bags as a whole. The only article published so far on consumer perception of shopping bags written on the basis of the attributes of shopping bags, is restricted to plastic and paper bags (Prendergast, et al., 2001). A large number of studies have been conducted to investigate the LCA of various shopping bags (Ellis et al.,2005; Chaffee and Yaros, 2007; Carrefour, 2004; Ecobilan, 2008; FRIDGE; www.sustainability-ed.org; Franklin Study; GUA, 2005; Los Angeles County Department of Public Works, 2007; Nolan ITU et al., 2002; ExcelPlas Australia et al., 2004; James and Grant, 2005; The ULS Report, 2008; McGrath; Muthu et al., 2009 ; Muthu et al., 2010b). Most of the studies focus on plastic and paper bags. However, very little work has been done on nonwoven and woven bags compared to plastic and paper bags. Studies of life cycle audits of shopping bags to obtain the primary data for LCI by conducting a field study in a manufacturing factory have not been conducted. The identification of hot-spots in the production processes/any life cycle phase of shopping bags has not been attempted either. Since currently available life cycle assessment software originates from Europe, life cycle impacts correspond to an average European or an average individual of the whole world in general were quantified and so far there has been no attempt to quantify the impacts specifically pertaining to Chinese consumers.

One of the major factors which decide the destiny of a product in terms of its eco-impact is its end-of-life scenario. This applies to all products and shopping bags. The end-of-life phase is as equally detrimental as the manufacturing phase for products like shopping bags which have a short life time. Some of the previous studies (Ellis et al., 2005; Chaffee and Yaros, 2007; Carrefour, 2004; Ecobilan, 2008; FRIDGE; www.sustainability-ed.org; Franklin Associates, 1990; GUA, 2005; Los Angeles County Department of Public Works, 2007; Nolan ITU et al., 2002; ExcelPlas Australia et al., 2004; James and Grant, 2005; The ULS Report, 2008; McGrath) dealt with LCA comparison of different shopping bags and have raised certain issues and concerns. Most of these studies included an end-of-life assumption to model the LCA of shopping bags. However, none of them used real data of recycling/reuse/landfill options, taken from the consumers of shopping bags. This is an interesting omission, which needs attention.

2.3.4. Test methods for shopping bags

Three Chinese national standards describe the various test methods to be followed for plastic shopping bags (GB 21660, 2008; GB 21661, 2008; GB 21662, 2008). The three standards are: GB 21660-2008, "General Requirements for Environmental Protection, Safety, Identification, and Marking of Plastic Shopping

Bags;" GB/T 21661-2008, "Plastic Shopping Bags;" and GB/T 21662-2008, "Quick Testing Method and Evaluation for Plastic Shopping Bags." The new standards became effective June 1, 2008.

Though many test methods are available for plastic shopping bags from the standards and also certain tests can be conducted on shopping bags from the tests discussed above in 2.1 and 2.2, there are no test methods and instruments available to scientifically evaluate the reusability property of shopping bags.

There are no studies on the biodegradability of reusable bags or on evaluating all of the shopping bags on a same platform.

There are no methods/models available to evaluate the recyclability of different textile materials/raw materials used for shopping bags.

2.4. Knowledge gaps

From the reviewed literature, it is understood that the following knowledge gaps exist:

1. Though quite a number of test methods have been available to evaluate the environmental (eco) and functional characteristics of textile materials or any products, no model has been developed to quantify the eco-functional properties of them. There seems to be little attempt among researchers to combine these closely related properties in an integrated platform by means of modelling to quantify the combined properties of textiles.

2. Currently there are no scientific models available to quantify the textile fibers/raw materials used for shopping bags to quantify their environmental impact and ecological sustainability in terms of both positive and negative impacts.

3. Very little focus has been given to reusable bags and studies focusing on life cycle audit of shopping bags to gather primary data for LCI for production processes. Hot-spots in the manufacturing processes have not been identified so far and life cycle impacts of shopping bags have not been quantified for Chinese consumers.

4. There are no instruments available to date to scientifically evaluate the reusability, impact strength and weight-holding capacity of shopping bags.

5. Consumption behaviour is one of the primary elements in deciding the life cycle impacts, which is in turn decided by the functional properties of products. No attempt has been made to date to combine functionality of the products and consumer behaviour. None of the previously published LCA studies on shopping bags have used real data of recycling/reuse/landfill options, taken from the consumers of shopping bags, to quantify the life cycle impacts.

6. There are no studies available reporting on the biodegradability of reusable bags or on evaluating all shopping bags on the same platform. Also, there are no models currently available to quantify the recyclability potential of different textile fibres/other raw materials used for shopping bags.

7. No attempts have yet been made to derive the index values of ecological, functional and eco-functional properties of textile materials/shopping bags and model them. Also with special reference to shopping bags, to date the life cycle impacts

(carbon footprint and eco-damage) pertaining to each life cycle phase from cradle to grave has not been addressed.

2.5. Objectives of the research work

The aim of this research work is to fill the knowledge gaps by a systematic study on developing an eco-functional modelling system to quantify the eco-functional properties of textile materials/shopping bags. The construction and development of this model was based extensively on mathematical models and simple logic models, various functional and environmental impact assessment testing methods, life cycle assessment techniques and their associated models. This research has the following principal objectives:

1. To develop a theoretical framework for "Eco-functional Assessment".
2. To develop a framework/model to quantify the environmental impact of different textile fibres and to position them in terms of environmental impact and ecological sustainability and also to analyse the life cycle inventory of the raw material phase of textile materials/ shopping bags.
3. To perform a life cycle audit on the shopping bag manufacturing processes to demonstrate methods of gathering primary data and also to identify and investigate the hot-spots in the manufacturing processes of shopping bags. Also there is an aim to quantify the life cycle impacts of shopping bags pertaining to consumers in China.
4. To evaluate the functional properties of different shopping bags with the available test methods and to develop a test method and an instrument to

evaluate the reusability, impact strength and weight-holding capacity of shopping bags. There is also a study of the consumption behavior of shopping bags in Mainland China, Hong Kong and India by a questionnaire survey study. This gathered the actual data of recycling/reuse/landfill options of various shopping bags which will be used to model the end-of-life scenario in LCA calculations. The survey was mainly done to study the relationship between the consumer behaviour and functional properties.

5. To evaluate the biodegradability of various shopping bags on the same platform and also to develop a framework/model to quantify the recyclability potential index of different textile fibres and to position them in terms of their recyclability potential.
6. To develop a comprehensive eco-functional assessment model and to quantify the "Eco-functional" score/grade of various shopping bags with the aid of the developed model. Finally, to ascertain the life cycle impacts (carbon footprint and eco-damage) of each phase in the life cycle of various shopping bags.

2.6. Research methodology

To achieve the objectives of this research, the following research methodologies are employed:

1. Development of theoretical framework

The aim here was to frame a background to evaluate the eco-functional properties of textile materials or any product by considering the raw material stage, processing sequences and functional and ecological properties. Four inputs and five outputs, which have the potential to illuminate eco-functional characteristics, were selected and their interrelations described in Chapter 3.

2. Development of a model for quantification of environmental impact and ecological sustainability for different textile fibres and other raw materials used for shopping bags

The aim of this second stage was to develop a unique model to quantify the environmental impact made by various textile fibres and to position them in terms of ecological sustainability. This model was developed to evaluate a wide range of textile fibres and also other raw materials used for the production of a popular variety of shopping bags by considering the major contributing factors in terms of environmental impact during the manufacturing phase (starting from growth /extraction stage to production of a useful fibre which can be spun). Consideration of environmental impact and ecological sustainability involved analysis of: the amount of oxygen produced/ carbon dioxide absorbed consequently contributing to off-set global warming during the production phase of a fibre, utilisation of renewable resources, land use, usage of fertilisers and pesticides, fibre/raw material recyclability and biodegradability. The life cycle inventory of various raw materials for textile products and shopping bags was also analysed and is addressed in Chapter 4.

3. Life cycle inventory and assessment of production phase of shopping bags

One of the major components of this research is Life Cycle Assessment (LCA). This phase involves the clear understanding of the technology of LCA and the detailed calculations and various methods pertaining to Life Cycle Inventory (LCI) and Life Cycle Impact Assessment (LCIA) stages. Life cycle inventory details were collected for various shopping bags exclusively for their production phase from secondary data sources.

Life cycle audit was conducted in a factory producing nonwoven shopping bags to gather comprehensive primary life cycle inventory data for nonwoven shopping bags and also to identify the hot-spots in the manufacturing processes of nonwoven shopping bags, which were revealed by conducting the carbon footprint and eco-damage assessment study. An attempt was also made to quantify the life cycle impacts of various shopping bags pertaining to consumers in China. This section is explained in Chapter 5.

4. Assessment of functional properties of shopping bags and consumer behaviour

The applicability of eco-functional textiles model was tested by evaluating the Eco-functional properties of various shopping bags. Different types of shopping bags were tested for their material composition, functionality, safety & bio functional properties and also for their environmental impact (eco) aspects. Suitable test methods were developed to evaluate the various shopping bag types and an instrument was developed to evaluate the reusability, impact resistance and the load bearing capacity of different shopping bags.

Consumer behaviour on using different shopping bags was studied by a questionnaire survey method conducted among various user groups in Mainland China, Hong Kong and India. This survey data, which helps to reveal the reality of bag use, was used for the end-of-life modelling phase in LCA calculations. The relationship/influence of consumer behavior was assessed in terms of functional properties. This part is explained in detail in Chapter 6.

5. Biodegradability studies and development of a model for quantification of Recyclability Potential Index (RPI) for different textile fibres and other raw materials used for shopping bags

A biodegradability study was conducted to study the biodegradability of different shopping bags on the same platform. Many types of fibers are used to manufacture textile products for daily use and they need to be recycled at the end of their lives. The potential recyclability of different fibres varies greatly from one fibre to another and many factors play a major role in deciding the recyclability of textile fibres. The concept for the recyclability potential index (RPI) of textile fibers considering their environmental and economic gains from the recycling process is proposed and also an attempt was made to quantify the recyclability potential index (RPI) of ten common and widely used textile fibers and other raw materials used for the production of popular variety of shopping bags. Chapter 7 deals with these aspects in detail.

6. Development of an integrated eco-functional assessment and an eco-functional assessment combined with life cycle assessment models

In this phase, a comprehensive eco-functional assessment model was developed and the "Eco-functional" scores achieved by various shopping bags were evaluated using the developed model. From the comprehensive life cycle inventory details collected in the different phases of the life cycle (i.e. raw material, production, functional properties, consumption and disposal), carbon, ecological footprints and eco-damage were assessed for each phase separately and for the whole life cycle of various shopping bags are also presented. Four research questions were formulated made to analyse the degree of influence of each phase in impacting the final result of carbon, ecological footprints and eco-damage assessment results and these are explored in Chapter 8.

2.7. Significance and originality of the research work

Considering the knowledge gaps discussed above, the originality of this study is to develop a systematic scientific framework for an Eco-functional model to quantify the Eco-functional properties of textile materials or any products. The focus of this study primarily lies on evaluating the Eco-functional properties of various types of shopping bags – plastic, paper, nonwoven and woven shopping bags and will quantify the Eco-functional properties by deriving an "Eco-functional" score for the various shopping bags under consideration. Considering this Eco-functional model as a platform, the environmental impact and ecological sustainability of different textile fibres can be quantified and they can be positioned in terms of their ecological sustainability. With the aid of this model, different textile fibres can be evaluated by the recyclability potential index (RPI).

This research deals with the comprehensive life cycle assessment of the different shopping bags under consideration. Life cycle inventory details were collected for each phase of shopping bags, including the use and disposal phases and their influence by the various functional and ecological properties of shopping bags. Life cycle audit was conducted to obtain the primary data for LCI and identify hot-spots in manufacturing, which were assessed by carbon footprint and eco-damage assessment methods. This was demonstrated by a case study conducted in a factory manufacturing nonwoven shopping bags. In addition, this research presents the quantified environmental impact values of different shopping bags, relating to consumers in China.

A new instrument has been developed in this study to quantify the reusability, impact strength and weight-holding capacity of various shopping bags, which will be of significant use to the manufacturing industries of various shopping bags.

Consumer behaviour was studied by conducting a questionnaire survey in Mainland China, Hong Kong and India to obtain the values to model the end-of-life scenario in LCA calculations. The influence of functional properties on consumer behaviour and the relationship between functional, ecological aspects and consumer behaviour were also studied, which is one of the primary focuses of this research study. Influence of each phase of life cycle in the final impact assessment results was demonstrated by four research questions to reveal the interaction of functional, ecological properties and consumer behaviour.

Though the Eco-functional concept was evaluated by shopping bags, it can be applied to any textile material and the "Eco-functional" score of any textile material can be determined. The outcome of the research will be valuable in developing a numerical engineering framework to quantify the eco-functional properties of any product in the category of textiles. This will be highly beneficial to shopping bag manufacturers and also to the textile community as a whole.

2.8. Conclusions

This chapter presented the details of the systematic literature review conducted for the study and the knowledge gaps identified. Objectives, research methodology, originality and significance of this research were also discussed in detail in this chapter.

The following chapter will discuss the theoretical framework developed for eco-functional assessment with the relevant inputs and outputs.

Chapter 3 Development of theoretical framework

3.1. Introduction

As discussed in Chapter 2, there are currently no models to quantify the eco-functional properties of textile materials or any other products and so this chapter will discuss the concept of eco-functional assessment and provide details of the development of a theoretical framework for such textiles or any such products. This chapter also describes the framework, gives details of various inputs and outputs used and suggests ways of connecting different inputs and outputs.

3.2. Development of theoretical framework

This study revolves around the concept of Eco-functional assessment, which is the central region formed by three interrelated aspects, i.e. functional, ecological properties and consumption behaviour. The basic concept of eco-functional assessment, which is the interaction among these three aspects, is depicted in Fig.3-1. Interrelation and interaction of all these aspects form the essence of eco-functional assessment and is studied systematically in this research. Influence of manufacturing process on the environmental impact is well established (Violet coloured in Fig.3-1); however, the influence of functionality on manufacturing process and also the consumption behaviour (Blue coloured in Fig.3-1), which in turn influences the ecological impact, has not been studied and reported in the literature. This research aims to systematically study this aspect.

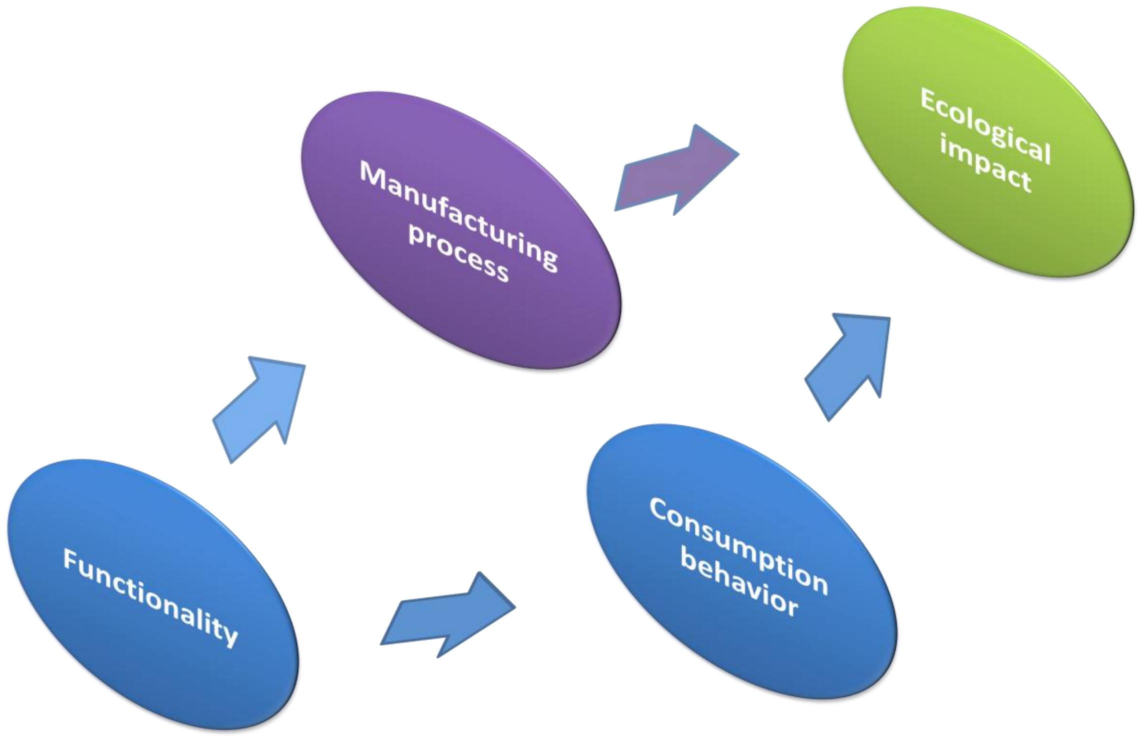


Figure 3-1 Basic concept of Eco-functional Assessment

The theoretical framework of Eco-functional assessment is illustrated in Fig. 3-2. As shown in Fig. 3.2, the traditional life cycle approach is well established (shown in green colour) and can be applied to assess the environmental impact of any product. However, textile products consist of a lengthy supply chain link, where in which the functionality of the product assumes significant importance in each phase of life cycle and hence the eco-functional approach is of certain importance to study the environmental impacts of the products (shown in blue colour in Fig.3-2), which is discussed in this research work.

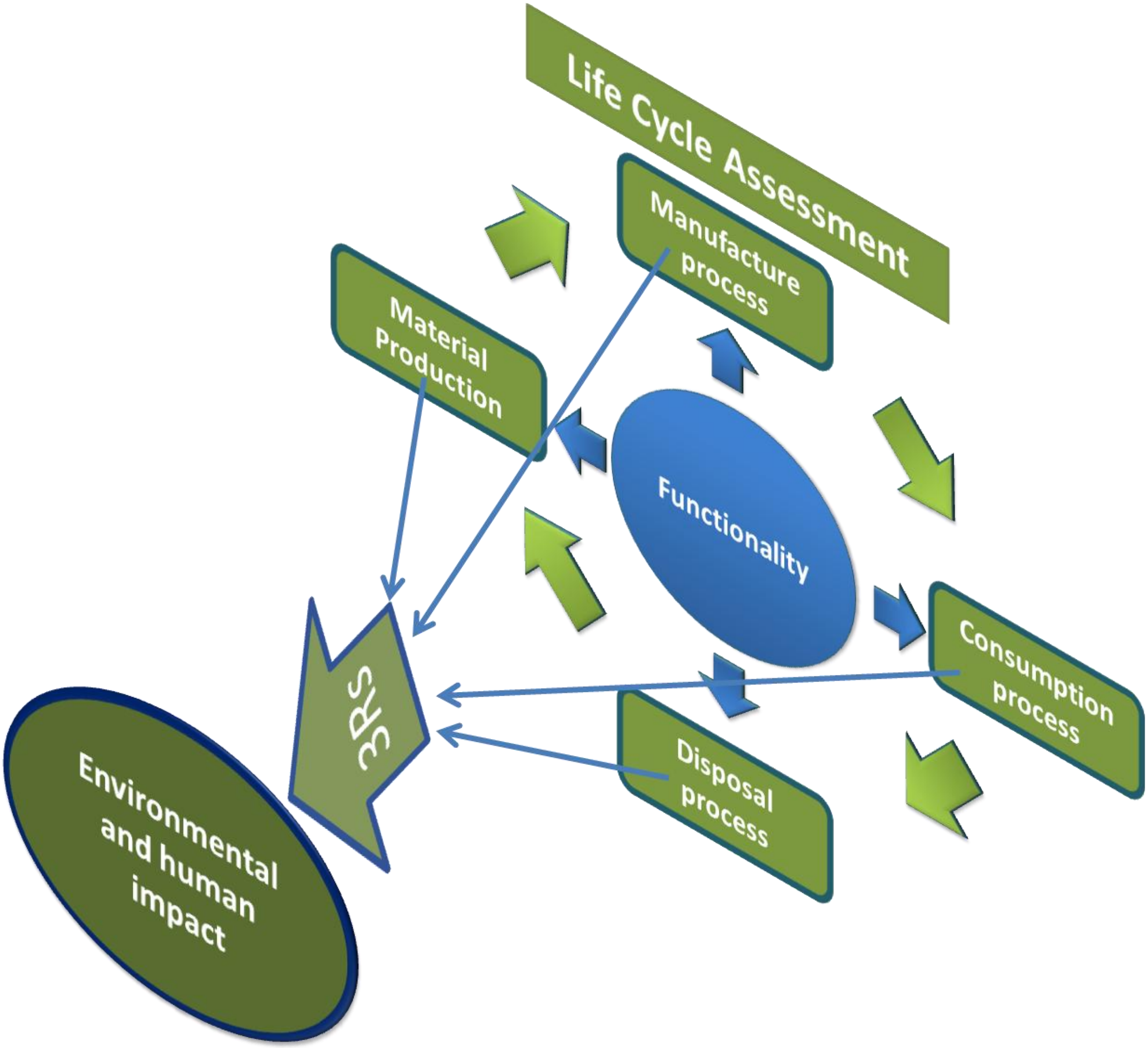


Figure 3-2 Theoretical framework of Eco-functional Assessment

(Note: Green Colour shows the traditional life cycle approach and the blue colour shows the eco-functional assessment approach).

As stated earlier, the concept of Eco-functional assessment is described by considering different types of shopping bags used for grocery purposes such as plastic, paper, nonwoven and woven bags made out of different raw materials. The eco-functional assessment model was developed based on the theoretical framework depicted in Fig.3-2 to evaluate the eco-functional properties of specific textile materials and products/shopping bags in this research and also to ascertain generally the eco-functional scores of any product. The eco-functional assessment model is comprised of four inputs and five outputs. The way the inputs and outputs are linked in this model is shown in Table 3-1.

Inputs	Outputs	Ways of Connection
1. Raw Materials	1. Human Impact 2. Environmental Impact	Both outputs are connected by a set of rules (Logical rules)
2. Process of Manufacture	1. 3Rs 2. Human Impact 3. Environmental Impact	1.3Rs by rules (Logical rules) 2.Human toxicity by formulae/ equations 3. Environmental impact by formulae/ equations
3. Functional Properties	1. Quality 2. Functionality	Both outputs are connected by rules (Logical rules)
4. Ecological Properties	1. 3Rs 2. Human Impact 3. Environmental Impact	Three are connected by a set of rules (Logical rules)

Table 3-1 Ways of connection of inputs and outputs

This model includes four inputs such as raw materials, process of manufacture, functional properties and ecological properties. It also includes five outputs such as quality, functionality, 3Rs, human impact and environmental impact, i.e. carbon footprint, ecological footprint and eco damage.

Formulae, methods and rules are established for the eco-functional model framework in accordance with the relevant international standards and/or industry standards and the theoretical model of the product life cycle approach. According to the results calculated from the developed model, it is possible to determine the quality and functionality of products and also to assess their impact on humans and the environment. It is also possible to analyze the potential of products to comply with the 3Rs (Reuse, Recycle and Reduce).

With the aid of the developed model, the eco-functional score/grade of any textile product can be derived. In this research, different types of shopping bags are considered to demonstrate the applications of the developed model.

3.2.1. Values of inputs: Modelling inputs

Fibre/Raw material

The first input is fibre/raw material used for the manufacture of the end product, i.e. shopping bags in this framework. Different types of raw materials are used to manufacture various types of shopping bags. A separate model has been developed to quantify the environmental impact and ecological sustainability of ten widely used textile fibres (conventional cotton, organic cotton, flax, wool, Nylon 6 and 66, polyester, polypropylene, acrylic and viscose) and other raw materials being used to manufacture popular variety of shopping bags (Low Density Polyethylene (LDPE), High Density Polyethylene (HDPE) and paper. Many factors have been taken into consideration to derive two numerical values: EI (Environmental Impact Index) and ESI (Ecological Sustainability Index) and the details of this model are explained in Chapter 4.

Process of manufacture

The second input involves consideration of the process of manufacture being employed to manufacture the end products. The different production processes employed to manufacture different types of shopping bags (plastic, paper, nonwoven and woven bags) need to be studied in terms of accounting for their comprehensive life cycle inventory. Some of the areas that need to be considered at this juncture are amount of raw materials employed, quantities of energy water, additives and other materials consumed, amount of airborne wastes, solid, liquid and other wastes emitted, etc.

Functional properties

The third input comprises the functional properties of shopping bags, which can be taken from the results of the tests, as shown in Table 3-2.

Material Composition	ISO 1833-1 (ISO 1833-1:2006)
Tensile strength and elongation of material	ASTM D 5034(Grab Test) (ASTM D5034 - 09)
Tear strength	ASTM D 1424 & 1922 (ASTM D1922 – 09; ASTM D1424 – 09)
Thickness	ASTM D1777 (ASTM D1777 - 96(2007)
Areal Density (Weight)	ASTM D3776 (ASTM D3776 / D3776M – 09)
Bursting strength	ISO 13938-2 (ISO 13938-2:1999)
Colour fastness to friction/rubbing	ISO105 X12 (ISO 105-X12:2001)
Colour fastness to water	ISO 105 E 01 (ISO 105-E01:1994)
Colour fastness to washing	ISO 105 C 06 -B2 (ISO 105-C06:2010)
Colour fastness to perspiration results –Acid & Alkali	ISO105 E 04 (ISO 105-E04:1994)
Colour fastness to light	ISO 105 B02 (ISO 105-B02:1994)
Impact Strength	Method and equipment developed in this research
Load carrying capacity /Weight-holding capacity	Method and equipment developed in this research
pH	ISO 3071 (ISO 3071:2005
Formaldehyde	ISO 14184-1 (ISO 14184-1:1998)
Waterproof	AATCC 127 (AATCC Test Method 127-2008

Air permeability	ISO 9237 (ISO 9237:1995)
Water Vapour Permeability	ASTM E 96 (ASTM E96 / E96M – 10)

Table 3-2 Functional properties of shopping bags

Ecological properties

The fourth input focuses on the ecological properties of shopping bags, which can be taken from the results of the tests given in Table 3-3.

Biodegradation of material	AATCC 30-Soil Burial Test (AATCC 30:2004)
Reusability	Method and equipment developed in this research
Recyclability	Method developed in this research

Table 3-3 Ecological properties of shopping bags

For the determination/quantification of recyclability, a separate model has been developed and this model aims to quantify the Recyclability Potential Index (RPI) of different types of raw materials considered for the production of shopping bags. The details of this model are described in Chapter 7.

3.2.2. Linking input and output variables

One of the key issues in this research work is the process of linking the various inputs and outputs selected for this model to evaluate any product in terms of its eco-functional characteristics. This part is explained in detail in Chapter 8.

3.3. Derivation of the Eco-Functional Index

With the aid of the developed model, it is also possible to derive an Eco-Functional Index/score (EFI) of any textile product apart from evaluating the suitability of products to sustain the requirements of the eco-functional assessment. In this step, a numerical score which can portray the capacity of the product in terms of its eco-functionality is derived. A separate index/index system is created from a grading scheme for each input and finally by combining the results of the indices from all four inputs, a final index, i.e. eco-functional index is derived. The steps to arrive at the final eco-functional index are discussed in detail in Chapter 8.

3.4. Development of an Eco-functional assessment combined with life cycle assessment (LCA) model

This thesis also includes the development of an eco-functional assessment combined with life cycle assessment (LCA) which deals with the different phases of the life cycle of a product, i.e. raw material extraction, production, functional properties, consumption and disposal phases. Life cycle inventory details will be collected for each of these phases for the entire life cycle of various shopping bags. These details are explained in the chapters that follow. With these details, carbon, ecological footprints and eco-damage will be assessed for each phase separately and the combined impact assessment for the entire life cycle will also be determined with the aid of one of the leading commercial softwares, SIMAPRO version 7.3.

Carbon footprint will be calculated by quantifying the $KgCo_2$ values for 100 years by IPCC 2007 GWP V 1.1, a successor of the IPCC 2001 method, developed by the Intergovernmental Panel on Climate Change. Ecological footprint will be evaluated by Ecological footprint method, version 1.00, which is directly taken from Ecoinvent 2.0. Eco-damage assessment will be performed by a damage oriented method, Eco-Indicator'99, Hierarchist method version 2.06.

Different research questions are formed in this research to study the degree of influence of each phase of life cycle on the final result, i.e. carbon, ecological footprints and eco-damage of various shopping bags. The research questions are formulated to be answered in the final part of the thesis (Fig. 3-3).

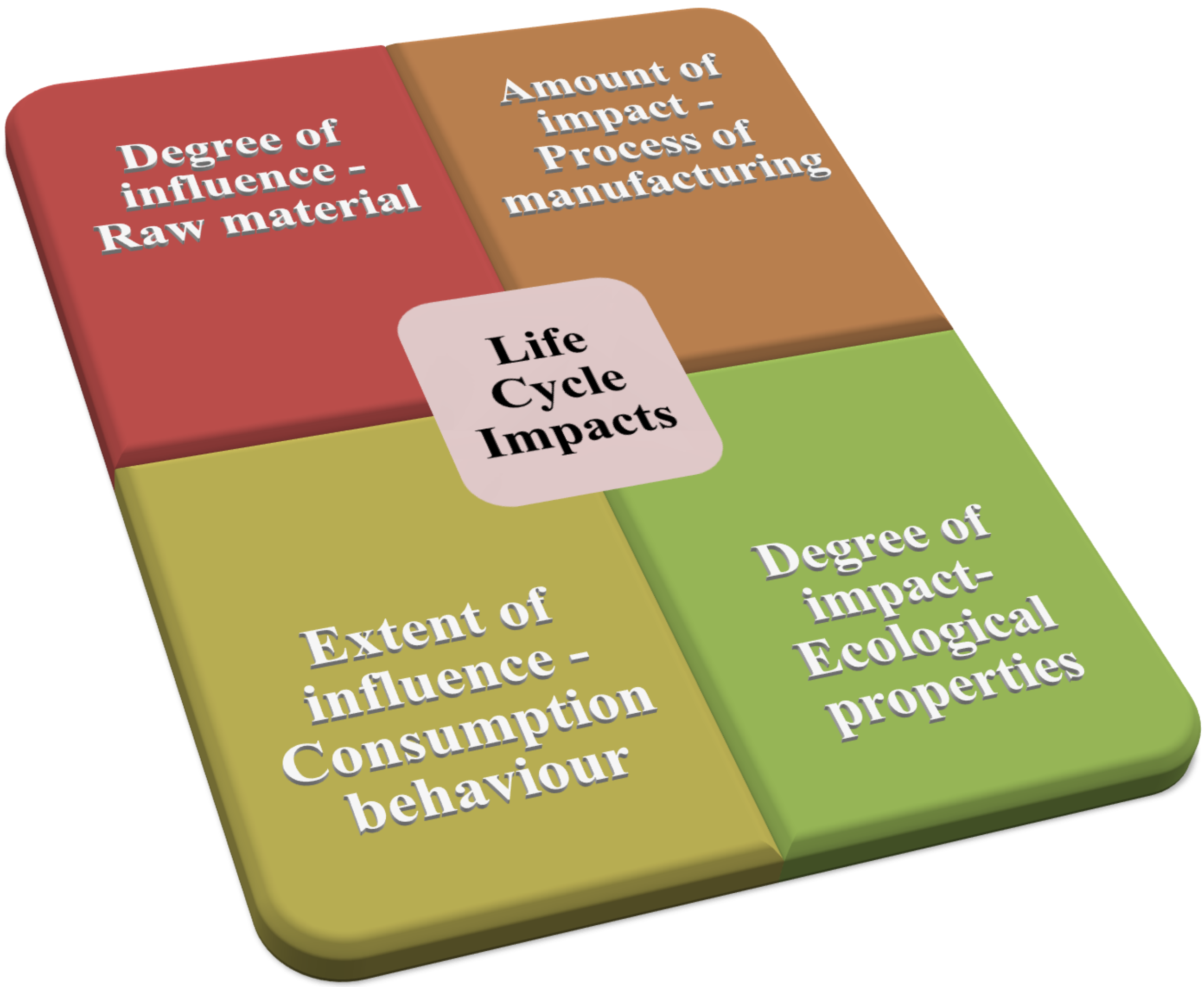


Figure 3-3 Research questions framed for this research study

Research question 1

It is commonly accepted that the type of fibre/ production processes of various fibres will influence the final result of LCA. However, it is not yet reported in the literature that what is the degree of influence? It is pivotal to scientifically quantify the level of influence of raw material on the final impact result. For this research question, relevant details of the life cycle inventory are discussed in Chapter 4.

Research question 2

The next phase of life cycle of shopping bags is the manufacturing phase of shopping bags from the fibre stage. This is the cradle to gate stage of shopping bags manufacturing phase. Though it is known that this phase has an impact on the carbon, ecological footprints and eco-damage results, but this is yet to be reported to what extent do they impact the results? This needs to be examined for the various shopping bags considered in this study. For this research question, relevant details of life cycle inventory are discussed in detail in Chapter 5.

Research question 3

An important, and to date unaccounted, phase of the life cycle of textile products and or shopping bags is the consumption behaviour, which is certainly influenced by the functional properties possessed by the textile materials/shopping bags. This research study makes an attempt to quantify the influence of consumer behaviour on the final impact result of LCA. Hence the following research question is posted to answer by a systematic study in this research work: does the consumption behaviour supplemented by the functional properties influence the final result; is so, what is the degree of influence?

The extent to which consumers think about their usage and disposal behaviour of various shopping bags needs to be studied and this can be experimentally verified by testing various functional properties of different shopping bags. From the experimental results, consumption behaviour results can be reexamined to test this research question. Study of consumption behaviour and testing of various functional properties of different shopping bags are discussed in Chapter 6. Details of the life cycle inventory pertaining to this third research question are discussed in detail in Chapter 6.

Research question 4

The final stage of a bag's life cycle is the disposal stage, which is the final destiny of materials. Shopping bags or textile materials will be disposed of at the end of the cycle. This has certain links with the research question dealing with usage and disposal behaviour. After it has been decided to dispose of the bags, they can be diverted to different options, and only recycling and disposal to landfill are considered in this study. Potential recyclability of various shopping bags along with their biodegradability is important factors that need to be considered at this juncture. Do these factors influence the carbon, ecological footprints and eco-damage results and to what extent do they impact the results? For this research question, relevant details of life cycle inventory are discussed in detail in Chapter 7.

3.5. Conclusions

In the present chapter, the theoretical framework of an eco-functional assessment model along with the details of different inputs and outputs used, and their interconnectedness are discussed. An evaluative method for textile products/shopping bags in terms of their eco-functionality is discussed in detail, as is the technique of quantifying the eco-functional index of a textile product/a shopping bag. Details of the development of a comprehensive life cycle assessment model based on a set of research questions that need to be tested were also discussed in this chapter.

The following chapter will discuss the life cycle inventory details for the raw material stage and also the development of a model to quantify the environmental impact and ecological sustainability of various textile fibres and other raw materials used for shopping bags. This chapter will present the relevant details pertaining to research question 1.

Chapter 4 Life Cycle Inventory of Raw Materials & Quantification of Environmental Impact and Ecological Sustainability for Textile Fibres and Other Raw Materials

4.1. Introduction

The following chapters (Chapters 4-7) will discuss the life cycle inventory details and analysis of each phase of textile materials/ shopping bags as discussed in Chapter 2. This chapter deals with the life cycle inventory details of different textile fibres and other raw materials used for shopping bags to test the first research question proposed in Chapter 3.

A knowledge gap was identified in Chapter 2: there is no unique model available at present to evaluate the different textile raw materials and other raw materials used for shopping bags in terms of their environmental impact and ecological sustainability. This chapter reports on the development of a unique model to quantify the environmental impact made by the various textile fibres and other raw materials, such as paper, low and high density polyethylene (LDPE, HDPE) used to produce shopping bags with reference to the current research and also to position them in terms of ecological sustainability. The major contributing factors in terms of environmental impact during the manufacturing phase (starting from the growth/extraction stage to the production of a useful fibre which can be spun) are selected to develop this model. In the first step, the following factors are considered: the amount of oxygen produced/carbon dioxide absorbed consequently contributing to off-set global warming during the production phase of a fibre, utilisation of renewable resources, land use, usage of fertilisers and pesticides, fibre recyclability and biodegradability of chosen fibres and other raw materials. In the second step, the amount of energy consumed, quantity of water utilised and amount of green house gases emitted are considered for the life cycle inventory (LCI). A life cycle impact assessment (LCIA) study is also conducted to derive certain impact categories pertaining to the damage caused to human health, ecosystem quality and resources. The LCIA will elucidate the characteristics of ecological sustainability. A scoring system based on the above mentioned factors, which predominantly determine ecological sustainability is framed, from which an Environmental Impact Index (EI) is developed. Further, an Ecological Sustainability Index (ESI) is derived from the EI values for the chosen fibres and other raw materials. According to this system, organic cotton is the most preferred fibre and acrylic the least. A sensitivity study was also conducted to check the robustness of the developed model and the results are reported.

4.2. Life Cycle Assessment

As discussed in section 2.2.5, life-cycle assessment (LCA) is an analytical tool which can help in understanding the environmental impacts from the acquisition of raw materials to final disposal (SETAC, 1993; Fava et al., 1991). According to ISO 14040 and ISO 14044, an LCA study essentially consists of four interconnected steps/phases (ISO 14040, 2006; ISO 14044, 2006):

- Goal and scope definition – Purpose, boundary definition and functional units assumed for the study.

- ❖ Inventory analysis – Analysis of material and energy; Accounting of different inputs and outputs used for the manufacturing of the product.
- ❖ Impact Assessment – Assessment of potential impacts by characterizing, normalizing, weighing different environmental impacts of the product.
- ❖ Interpretation – Analysis of results with suggestions and recommendations to mitigate detrimental impacts.

4.2.1. Life Cycle Inventory Analysis

As stated in section 2.2.5, the LCI stage focuses on analyzing the different flows of material and energy corresponding to the production of the product and the respective impacts on the environment. The data pertaining to the flows of input and output are collected in this phase (ISO 14040, 2006; ISO 14044, 2006), as shown in Fig.2-6.

4.2.2. Life Cycle (LCI) of Textile Fibres and other raw materials used for shopping bags

This section analyses the LCI of different textile fibres and other raw materials used to produce shopping bags. Though many factors can be considered as LCI, three important factors in the fibre stage namely energy needs, water needs and CO_2 emissions are considered in this research. These significant factors essentially reflect the environmental impact and the ecological sustainability of any material. Cradle to gate data for raw material production of different textile fibres and other raw materials were collected for shopping bags from different secondary data sources are discussed below.

Energy needs

Energy is one of the major factors which influence the ecological sustainability of fibres and other raw materials. The discussion is confined to artificial energy sources employed in fibre/raw material production, not natural sources of energy such as the energy derived from sun light in the fibre growth stage. The amount of energy needed to produce one kilogram of fibre/raw material is tabulated in Table 4-1 for various fibres.

Fibres and other raw materials	Energy use in MJ per kg. of fibre/raw material
Conventional Cotton	60.0 (Kaillala and Nousiainen, 1999)
Organic Cotton	54.0 (Kaillala and Nousiainen, 1999)
Flax	10.0 (Oecotextiles)
Wool	63 (Barber and Pellow, 2006)
Viscose	100.0 (Barber and Pellow, 2006)
Polypropylene	115.0 (Barber and Pellow, 2006)
Polyester	125.0 (Barber and Pellow, 2006)
Acrylic	175.0 (Barber and Pellow, 2006)
Nylon 66	138.7 (Boustead, 2005)
Nylon 6	120.5 (Boustead, 2005)
Paper	21.6 (Going Carbon Neutral)
LDPE	78.1 (Boustead, 2005)
HDPE	76.7 (Boustead, 2005)

Table 4-1 Energy needs to produce one kilogram of fibre/raw material for shopping bag (results rounded-off)

For natural fibres/other raw materials, the energy need is the amount of energy required in mega joules in the production of a particular fibre in a mill (field to mill gate); in the case of synthetic fibres/other raw materials, it is the energy utilised from raw material extraction to the polymerisation stage (to the conversion of spinnable fibre). It is evident from the data that fibres of natural origin consume less energy for production than synthetic fibres.

Water requirements

The next factor, which is as significant as energy needs in determining ecological sustainability, is the water essential for the production of fibre/other raw materials. Table 4-2 lists the water requirements to produce one kilogram of textile fibre/other raw materials. The water requirements of conversion to a useful fibre stage or raw material are indicated. For natural materials of plant and animal-origin, the water requirements from the initial stage to the mill stage and in case of synthetic materials water needs from raw material extraction to the fibre production stage are indicated here.

The data clearly indicate that cotton, both conventional and organic, consumes an enormous amount of water during production compared to its natural and synthetic counterparts. Water requirements listed in Table 4-2 include both processing and cooling needs.

Fibres and other raw materials	Water requirement per kg. of fibre/raw material
Conventional Cotton	22000 kgs. (Kaillala and Nousiainen, 1999)
Nylon 6	185 kgs. (Boustead, 2005)
Flax	214 Litres (Laursen et al., 1997)
Polypropylene	43 kgs. (Boustead, 2005)
Polyester	62 kgs. (Boustead, 2005)
Nylon 66	663 kgs. (Boustead, 2005)
Organic cotton	24000 kgs. (Kaillala and Nousiainen, 1999)
Wool	125 L; 5-40 Litres (Scouring) (Laursen et al., 1997)
Viscose	640 Litres (Laursen et al., 1997)
Acrylic	210 Litres (Laursen et al., 1997)
Paper	300 Litres (Going Carbon Neutral)
LDPE	47 kgs. (Boustead, 2005)
HDPE	32 kgs. (Boustead, 2005)

Table 4-2 Water requirements to produce one kilogram of fibre/raw material for shopping bag

CO_2 emission from fibres (cradle to gate of fibre)

The factor of green house gas (GHG) emissions is also one of the main factors to be assessed in determining ecological sustainability. The main greenhouse gases in the earth's atmosphere are water vapor, carbon dioxide, methane, nitrous oxide, ozone and CFCs (Green House Gas). The major effect of these gases is global warming (Global Warming), which is measured by "Global Warming Potential" (GWP). This is a measure of how much a given mass of greenhouse gas is estimated to contribute to global warming (Global Warming Potential). Among all GHG's, Carbon dioxide is a reference for comparison with the GWP of other gases. The global warming potential of different green house gases can be referred to from the Inter Governmental Panel on Climate Change (IPCC) report (IPCC, 2001). In this paper the CO_2 emissions from fibres and other raw materials in their "cradle to gate stage" is considered only as a factor to determine ecological sustainability. GHG emissions are shown in Table 4-3.

Fibres and other raw materials	CO_2 Emission – kg CO_2 per kg. of fibre / raw material
Nylon 6	5.5 (Boustead, 2005)
Nylon 66	6.5 (Boustead, 2005)
Viscose	9.0 (Morris, 2010) (-3.5 for bio-mass credit)
Acrylic	5.0 (Morris, 2010)
Polyester	2.8 (Boustead, 2005)
Organic Cotton	2.5 (Kaillala and Nousiainen, 1999)
Wool	2.2 (Morris,2010)
Conventional Cotton	6.0 (Kaillala and Nousiainen, 1999)
Flax	3.8 (Cherett et al.,2005)
Polypropylene (PP)	1.7 (Boustead, 2005)
Paper	3.2 (Going Carbon Neutral)
LDPE	1.7 (Boustead, 2005)
HDPE	1.6 (Boustead, 2005)

Table 4-3 CO_2 emission- kg CO_2 per kg. of fibre /raw material for shopping bag (cradle to gate)

4.3. Environmental Impact and Ecological Sustainability of textile fibres and other raw materials

The concept of sustainability is not new and can be defined in numerous ways. A famous definition given by the World Commission on Environment and Development is "The development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Bruntland, 1987). Sustainability is being practised in most fields and it is an area of key concern across the globe. In a deeper sense, sustainability is the concept of using renewable or replenishable resources, so that we do not exhaust all our existing resources, causing the next generation to suffer.

The same concept, when applied to textiles, can be defined as producing textile products using raw materials, energy and other ingredients which are derived from renewable resources that cannot be exhausted and consequently do not affect the next generation. Similarly, a sustainable fibre is one which is manufactured/produced using raw materials and energy and is derived entirely from renewable resources (Bruntland, 1987).

Sustainability has many faces and facets, one of which is ecological sustainability, which is very closely linked to environmental protection. Environmental protection and sustainable development have been gaining greater attention and public importance in recent years. This is the present status in environmentally cautious societies where industries causing adverse changes to the immediate environment are being challenged by society (Thanikaivelan et al., 2005). One of the most important industries under environmental scrutiny is the textile industry.

Horrocks, et al., (1997) dealt with the assessment of textile products in terms of their environmental consequences by means of a simple life cycle analytical model. Their research mainly focused on the assessment of flame retardant textiles from the fibre stage to the disposal stage with subjective rankings given in the absence of complete empirical data. Although this study considers all aspects of textiles in terms of life cycle, there is still a dearth of information about the objective assessment of different fibres. Surprisingly, very little research has been carried out to assess the currently available fibres and other raw materials in terms of their ecological sustainability and particularly by considering the ecological benefits gained by the fibres and other raw materials due to photosynthesis. This is an interesting and unexplored part of the field of ecological assessment of textile fibres. Even though currently available life cycle models address numerous factors, some major factors, such as recyclability, biodegradability and the inclusion of positive effects of plants and trees in off-setting global warming, that have not been given due consideration. Hence there is a need for the development of a comprehensive model that includes all factors to determine the ecological sustainability of textile fibres and other raw materials.

To fill these knowledge gaps, this research evaluates various textile fibres and other raw materials by means of a specifically developed model in terms of such factors as their photosynthesis effect, utilisation of renewable resources, land use, usage of fertilisers and pesticides, fibre recyclability and biodegradability, energy and water needs and green house gas emissions. These factors reflect the extent of ecological sustainability of fibres and other raw materials and augment our current limited knowledge of unifying various fibres and other raw materials for the production of shopping bags under the criteria of ecological sustainability. An important point to be noted at this juncture is that the entire discussion is confined to fibres and other raw materials in their initial stage (from cradle to gate), where are the materials are ready to be spun into yarn/processed forward to the next step of manufacturing. In other words, the eco-profiles of different fibres and raw materials are taken into consideration.

Ten important fibres, namely conventional cotton, organic cotton, wool, flax, polyester, nylon 6, nylon 66, polypropylene, acrylic and viscose and other raw materials such as paper, low density and high density polyethylene employed to manufacture paper and plastic shopping bags are chosen for study of their ecological sustainability.

4.4. Quantification of environmental impact and derivation of ecological sustainability index- Derivation of equations

The major aims of the model are to quantify the environmental impact made by textile fibres and other raw materials and to derive an Environmental Impact Index (EI) and an Ecological Sustainability Index (ESI). The structure of the developed model is depicted in Fig.4-1 and the corresponding equations are given in equations 1 and 2. Firstly, the photosynthesis effect (amount of oxygen produced), utilisation of renewable resources, land use, usage of fertilisers and pesticides, fibre recyclability and biodegradability are considered. Secondly, energy, water requirements and CO_2 emissions are considered and the relevant values are studied. Thirdly, considering these factors as a life cycle inventory, a life cycle impact assessment (LCIA) is carried out and certain impact categories, such as damage to human health, ecosystem quality and resources, which determine ecological sustainability, are chosen. A scoring system is then developed based on the values of all the factors discussed and the values of the impact categories are calculated from the LCIA. Summation of scores in each category resulted in a single score called the “Environmental Impact index (EI)” (equation 1) and from the EI, an “Ecological Sustainability Index (ESI)” is derived, which is expressed in equation 2. Aggregation of the values of above mentioned factors are fitted into the equation 1 with weighing co-efficients to perform the sensitivity study to test the robustness of the model developed and the validity of the equations.

The ecological sustainability index can be mathematically expressed as follows:

$$EI = \sum \alpha_j Y_j = \alpha_1 Y_1 + \alpha_2 Y_2 + \alpha_3 Y_3 + \alpha_4 Y_4 + \alpha_5 Y_5 + \alpha_6 Y_6 + \alpha_7 Y_7 \quad (1)$$

$$ESI_k = (1 - EI_k / EI_{max}) \times 100 \quad (2)$$

where,

EI – Environmental Impact index

EI_k – Environmental impact index of the k^{th} fibre under consideration

EI_{max} – The gained maximum scores of Environmental impact index among the selected fibres

ESI –Ecological Sustainability Index

ESI_k – Ecological Sustainability Index of the k^{th} fibre under consideration

α_j – Weighting coefficient for the j^{th} factor

Y_1 –O_2 emission / CO_2 absorption in fibre production

Y_2 – Use of renewable resources in fibre production

Y_3 – Land use in fibre production

Y_4 – Usage of fertilizers & pesticides in fibre production

Y_5 – Fibre recyclability

Y_6 – Fibre biodegradability

Y_7 – EI_{LCIA} - LCIA Impact categories, which is defined as

$$Y_7 = \sum \beta_i X_i = \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3$$

$$(X_1, \ldots X_3) = f\,(x_1, x_2, x_3), \text{ i.e. } X_1 = f_1(x_1, x_2, x_3)$$

β_i – Weighting coefficient for the i^{th} LCIA indices

X_1- Damage to Human Health

X_2– Damage to Eco System Quality

X_3- Damage to Resources

x_1– Energy consumption in fibre production

x_2 – Water consumption in fibre production

x_3 – CO_2 Emissions in fibre production

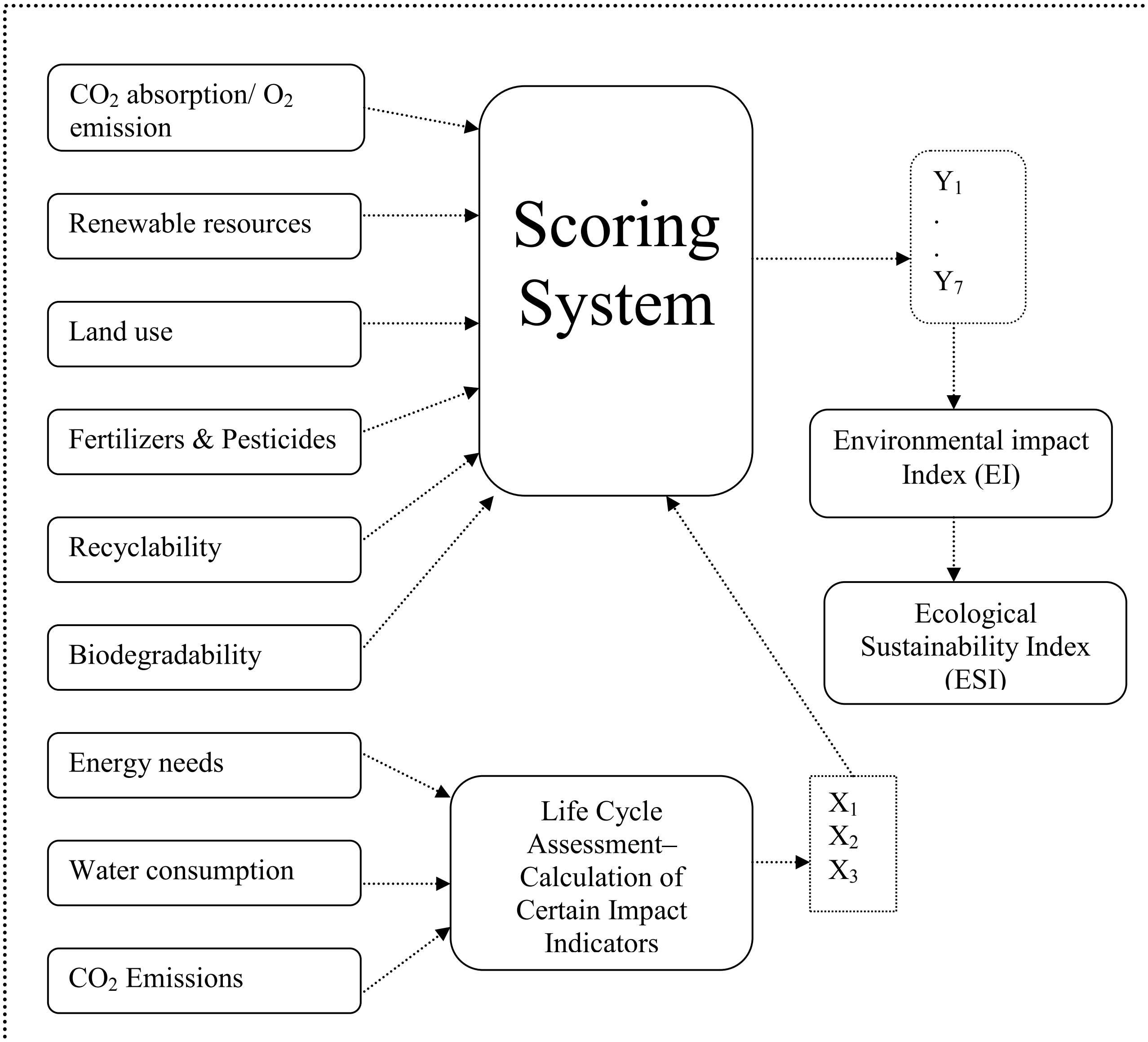


Figure 4-1 Structure of environmental impact and ecological sustainability model

4.4.1. Scoring system for Environmental Impact index (EI) of fibres

Firstly, based on the data pertaining to photosynthesis effect (amount of oxygen produced), utilisation of renewable resources, land use, usage of fertilisers and pesticides, fibre recyclability and biodegradability, a set of scoring system (consisting numerical scores of 0-5 in all cases, except for photo synthesis effect (-1 to 5), based on the available results is developed. Secondly, based on the LCIA results on the extent of damages created to human health, ecosystem quality and resources, another set of scoring system (consisting numerical scores of 0-5 based on the available results) is developed. The scoring system corresponding to each category ($Y_1 \ldots Y_7$) is explained in detail below under the relevant sections. As described in equation 1, EI is derived as the summation of Y_1, Y_2 ...Y_7. The higher the EI, the higher is the impact on the environment.

4.4.2. Derivation of Ecological Sustainable Index

As explained in equation 2, ESI can be derived from the EI of a fibre and other raw materials by dividing the EI of the fibre under consideration by the maximum EI derived among all the selected fibres and other raw materials, and a higher ESI implies lower environmental impact, hence a more sustainable environment.

4.5. Data acquisition and Calculation

4.5.1. Amount of oxygen produced

The foremost factor to be considered which determines ecological sustainability is the amount of oxygen released to the atmosphere. It is a renowned fact that there exists a process which converts CO_2 into organic compounds such as sugar, by consuming energy from sunlight in the presence of water, during this process besides sugar; Oxygen is released as a byproduct. The Oxygen produced is essential for life on earth for all living organisms (Photosynthesis). A general equation (Equation for Photosynthesis) which represents this reaction is given below:

$$6CO_2 + 6H_2O + \text{Energy} \longrightarrow C_6H_{12}O_6 + 6O_2$$

This is a bounty to humanity from plants (so are the fibres derived from these plants). This effect primarily needs to be recorded and considered for determining ecological sustainability. CO_2 is eventually absorbed during the process and this consequently reduces global warming. These effects are calculated for textile fibres and other raw materials made out of such resources.

Table 4-4 enumerates the values of different fibres and other raw materials under the categories of oxygen released / amount of CO_2 absorbed during photosynthesis. The whole effect of photosynthesis is very particular to fibres and other raw materials extracted from natural resources such as plants and trees. All the other fibres and other raw materials of both animal and synthetic origins do not come into picture and they only emit green house gases such as CO_2 and methane [emitted by sheep] (www.climateark.org), which largely contribute to global warming. Keeping that in mind, the scoring system pertaining to this category is depicted in Fig. 4-2 and the relevant score of each fibre in Table 4-5.

Fibre / Other raw materials	Amount of oxygen released	Amount of CO_2 absorbed
Cotton	8000 kgs/ hectare (Jordan, 2009)	11000 kgs/hectare/yr 23404 kg/acre (Jordan, 2009)
Hemp	(Data Not Available).	2500 kgs/hectare (Mankowski and Kolodziej, 2008) 5319 kgs/acre (Mankowski and Kolodziej, 2008)
Viscose	2800 O_2/acre/year (Benefits of Trees in Urban Areas)	1000 kgs/acre (Benefits of Trees in Urban Areas)

Paper	(Data Not Available).	1000 kgs/acre (Benefits of Trees in Urban Areas)

Table 4-4 Amount of oxygen released / Amount of CO_2 absorbed during photosynthesis from plants and trees of fibres/raw materials for shopping bags

CO_2 absorption /emission

Amount of CO_2 absorbed / acre/year	Score
<1000	-1
1000-5000	-2
5000-10000	-3
10000-20000	-4
>20000	-5
Negative contribution – CO_2 emission	5

Figure 4-2 Scoring scheme for CO_2 absorption

Fibre / Other raw materials	Y_1
Cotton	-5
Organic Cotton	-5
Wool	5
Hemp	-3
Nylon6	5
Nylon 66	5
Polyester	5
PP	5
Acrylic	5
Viscose	-2
Paper	-2
LDPE	5
HDPE	5

Table 4-5 Value of O_2 emission / CO_2 absorption in fibre/raw material production

4.5.2. Renewable resources utilisation

This category examines the utilisation of renewable resources for the production of fibres and other raw materials. Renewable resources are ones which are replaced by natural processes at a rate comparable or faster than their rate of consumption by humans (Renewable Resource). With this background, textile fibres and other raw materials obtained from natural resources for instance plants, trees and animals are renewable (cotton, viscose, hemp and wool). On the other hand, fibres from petroleum sources and other resources (nylon, polyester, polypropylene, and acrylic) which cannot be renewed are non-renewable. The scoring scheme for this category and the corresponding value of each fibre and other raw materials are listed in Fig.4-3 and Table 4-6 respectively.

Fibre / Other raw materials	Renewable resources utilisation	Value of Y_2
Cotton	Yes (Chen and Burns, 2006)	0
Organic Cotton	Yes (Muthu et al., 2012d)	0
Wool	Yes (Chen and Burns, 2006)	0
Hemp	Yes (Muthu et al., 2012d)	0
Nylon 6	No (Chen and Burns, 2006)	5
Nylon 66	No (Chen and Burns, 2006)	5
Polyester	No (Chen and Burns, 2006)	5
PP	No (Chen and Burns, 2006)	5
Acrylic	No (Chen and Burns, 2006)	5
Viscose	Yes (Muthu et al., 2012d)	0
Paper	Yes (Muthu et al., 2012d)	0
LDPE	No(Muthu et al., 2012d)	5
HDPE	No(Muthu et al., 2012d)	5

Table 4-6 Value of renewable resources utilisation in fibre/raw material production

Resources	***Score***
Renewable	0
Non-renewable	5

Figure 4-3 Scoring scheme for resources

4.5.3. Land use

This factor takes into consideration the usage of land as a resource for the fibres and other raw materials to grow. Clearly, this factor is suitable for natural fibres and other natural raw materials of cellulosic and animal origin, since they need land for their growth and for further processing of the fibre into a useful textile product. As a matter of fact, even synthetic fibres and other raw materials from a synthetic origin need land for their production of their fibres and also they need land for building production facilities. This is a form of indirect land use. This category considers both direct and indirect usage of land for growth/production of fibres and other raw materials. In this light, the scoring scheme and the score of each fibre is shown in Fig. 4-4 and Table 4-7(Muthu et al., 2012d).

Fibre / Other raw materials	Use of Land	Value of Y_3
Cotton	Direct	5
Organic Cotton	Direct	5
Wool	Direct	5
Hemp	Direct	5
Nylon 6	Indirect	2.5
Nylon 66	Indirect	2.5
Polyester	Indirect	2.5
PP	Indirect	2.5
Acrylic	Indirect	2.5
Viscose	Direct	5
Paper	Direct	5
LDPE	Indirect	2.5
HDPE	Indirect	2.5

Table 4-7 Value of Land use in fibre/raw material production

Usage of Land	***Score***
Direct	5
Indirect	2.5

Figure 4-4 Scoring scheme for land use

4.5.4. Usage of synthetic fertilizers and pesticides

This category considers the practice of using fertilizers and pesticides for the growth of fibres and other raw materials. This factor is applicable to natural fibres, again fibres of plant origin and animal origin (sheep, for instance, needs pesticides in their feed or on pasture land). The scoring scheme and relevant value of each fibre can be seen in Fig. 4-5 and Table 4-8 (Muthu et al., 2012d).

Fibre / Other raw materials	Use of fertilizers and pesticides	Value of Y_4
Cotton	Yes	5
Organic Cotton	No	0
Wool	Yes	5
Hemp	Yes	5
Nylon 6	No	0
Nylon 66	No	0
Polyester	No	0
PP	No	0
Acrylic	No	0
Viscose	No	0
Paper	No	0
LDPE	No	0
HDPE	No	0

Table 4-8 Value of usage of fertilizers and pesticides in fibres/raw materials production

Usage of fertilizers and pesticides	***Score***
Yes	5
No	0

Figure 4-5 Scoring scheme for fertilizers and pesticides

4.5.5. Fibre Recyclability and Biodegradability

Fibre recyclability refers to the ability of the fibres and other raw materials to be recycled. Recycling refers to the conversion of the old products into new ones which are discarded after use. This process involves breaking down the old items and preparing the new products. This helps in the diminution of wastage of materials which have the potential to be used again and to trim the consumption of fresh raw materials and results in other associated benefits like reduced cost, energy, pollution (Muthu et al., 2010a). Fibres and other raw materials such as cotton, paper and viscose are difficult to recycle, and fibres like wool, nylon and polyester are easy to recycle (Chen and Burns, 2006). PP, LDPE, HDPE (Olefins) and acrylic are also difficult to recycle (Horrocks, et al., 1997).

As regards biodegradability, when textiles are buried in soil, soil-resident microorganisms take part in the degradation of textile materials; a process which is called biodegradation. Biodegradability is often used as a standard measurement of the environmental friendliness of textile products (Park et al., 2004). Fibres of natural origin such as cotton, wool and viscose are biodegradable (Chen and Burns, 2006) and nylon, polyester are non- biodegradable (Chen and Burns, 2006). PP, LDPE, HDPE (Olefins) and acrylic also fall into the non-biodegradable category (Horrocks, et al., 1997).

Fibre / Other raw materials	Recyclability	Value of Y_5	Biodegradability	Value of Y_6
Cotton	Difficult (Chen and Burns, 2006)	5	Yes (Chen and Burns, 2006)	0
Organic Cotton	Difficult (Chen and Burns, 2006)	5	Yes (Chen and Burns, 2006)	0
Wool	Easy (Chen and Burns, 2006)	0	Yes (Chen and Burns, 2006)	0
Hemp	Difficult (Muthu et al., 2012d)	5	Yes (Muthu et al., 2012d)	0
Nylon 6	Easy (Chen and Burns,	0	No (Chen and Burns, 2006)	5

	2006)			
Nylon66	Easy (Chen and Burns, 2006)	0	No (Chen and Burns, 2006)	5
Polyester	Easy (Chen and Burns, 2006)	0	No (Chen and Burns, 2006)	5
PP	Difficult (Horrocks, et al., 1997)	5	No (Horrocks, et al., 1997)	5
Acrylic	Difficult (Horrocks, et al., 1997)	5	No (Horrocks, et al., 1997)	5
Viscose	Difficult (Chen and Burns, 2006)	5	Yes (Chen and Burns, 2006)	0
Paper	Difficult (Chen and Burns, 2006)	5	Yes (Muthu et al., 2012d)	0
LDPE	Difficult (Horrocks, et al., 1997) (Olefin family)	5	No (Horrocks, et al., 1997)	5
HDPE	Difficult (Horrocks, et al., 1997)	5	No (Horrocks, et al., 1997)	5

Table 4-9 Values of Recyclability and biodegradability of fibres/raw materials

Recyclability	***Score***
With Ease	0
With Difficulty	5
Biodegradability	***Score***
Yes	0
No	5

Figure 4-6 Scoring scheme for recyclability and biodegradability

Fibre recyclability and biodegradability refer to end-of-life options and largely contribute to disposal issues like landfill. These factors also enable various products to be disposed/recycled in a safe manner and hence a special consideration is given in this model to these two factors. A scoring scheme was developed and the corresponding values of the fibres under discussion are shown in Fig.4-6 and Table 4-9.

4.5.6. EI_{LCIA} - LCIA categories

4.5.6.1. Life Cycle Impact Assessment of textile fibres and other raw materials

As stated earlier, a life cycle assessment (LCA) is an analytical tool which helps to explain the ecological impacts created from acquisition of raw materials to the final disposal stage (SETAC, 1993; Fava et al., 1991).

4.5.6.2. Life cycle inventory data

It is mandatory for the calculation of LCIA, to have life cycle inventory (LCI) data. As stated earlier, factors such as energy needs, water requirements and CO_2 emissions in the production stage of fibre and other raw materials were considered as LCI (as listed in Tables 4-1 - 4-3) and LCIA study was performed. These factors were chosen since they are primary considerations in the assessment of environmental impact and ecological sustainability.

4.5.6.3. Calculation of indicators by LCIA method

By considering the three factors for the life cycle inventory, i.e. energy needs, water requirements and CO_2 emissions in the production stage of fibre and other raw materials, life cycle impact assessment was calculated using SIMAPRO version 7.2 of LCA software (Life Cycle Impact Assessment). Among the various impact assessment methods (Life Cycle Impact Assessment Methods), Eco-indicator'99 (Hierarchist version) method was adopted to calculate the damage created by the fibres and other raw materials in the following categories. This can help to assess the environmental impact and the sustainability of the fibre production process:

I. Damage to Human Health (DALY) (Disability-Adjusted Life Years)

II. Damage to Eco System Quality (PDF*m2yr) (Potentially Disappeared Fraction of plant species)

III. Damage to Resources (MJ Surplus) (Additional energy requirement to compensate lower future ore grade)

The detailed working principle of the method can be found from the references (Ecoindicator' 99 method; Goedkoop et al., 2000 & 2001).

4.5.6.4. Results of Life Cycle Assessment indicators

LCIA was performed using Eco-indicator'99, H/H version method and the results are listed in Table 4-10. The scoring system based on the LCIA impact categories/indicators are depicted in Fig. 4-7 and the corresponding indices of this category are listed in Table 4-11.

Fibre / raw material	Damage to Human Health (DALY) (Scale:1000:1)	Damage to Eco System Quality (PDF*m2yr)	Damage to Resources (MJ Surplus)
Cotton	0.5	3.2	9.4
Organic Cotton	0.4	2.9	8.5
Wool	0.5	3.4	9.9
Flax	0.1	0.5	1.6
Nylon6	1.0	6.5	18.9
Nylon 66	1.1	7.5	21.7
Polyester	1.0	6.8	19.6
Polypropylene (PP)	0.9	6.2	18.0
Acrylic	1.4	9.5	27.4
Viscose	0.8	5.4	15.7

Paper	0.2	1.2	3.4
LDPE	0.6	4.2	12.2
HDPE	0.6	4.2	12.0

Table 4-10 Life cycle impact assessment results (results rounded-off)

Damage to Human Health (DALY)

<0.1	0
0.11- 0.3	1
0.31-0.6	2
0.61-0.9	3
0.91-1.2	4
>1.21	5

Damage to Eco System Quality (PDF*m2yr)

<0.5	0
0.6-2	1
2.1-4	2
4.1-6	3
6.1-8	4
>8.1	5

Damage to Resources (MJ Surplus)

<2	0
2.1-5	1
5.1-10	2
10.1-15	3
15.1-20	4
>20.1	5

Figure 4-7 Scoring system based on LCIA indicators

Fibre	Damage to Human Health	Damage to Eco System Quality	Damage to Resources	Value of Y_7
Cotton	2	2	2	6
Organic Cotton	2	2	2	6
Wool	2	2	2	6
Flax	0	0	0	0
Nylon6	4	4	4	12
Nylon 66	4	4	5	13
Polyester	4	4	4	12
PP	3	4	4	11
Acrylic	5	5	5	15
Viscose	3	4	4	11
Paper	2	1	1	4

LDPE	3	3	3	9
HDPE	3	3	3	9

Table 4-11 Values of LCIA indicators from fibre/raw material production

4.6. Results and Discussions

4.6.1 Environmental impact of different textile fibres and other raw materials

Utilizing the scoring schemes explained above, scores were calculated for the chosen ten fibres and paper, LDPE and HDPE are represented by the values of Y_1, $Y_2 \ldots Y_7$. According to equation (1), summation of all the scores in each category results in an index called the "Environmental Impact Index (EI)". The results of the values of Y_7 of different fibres are depicted in Fig.4-8. The EI values of ten fibres and other raw materials under consideration are shown in Fig.4-9 where all weighing co-efficients are considered as equal.

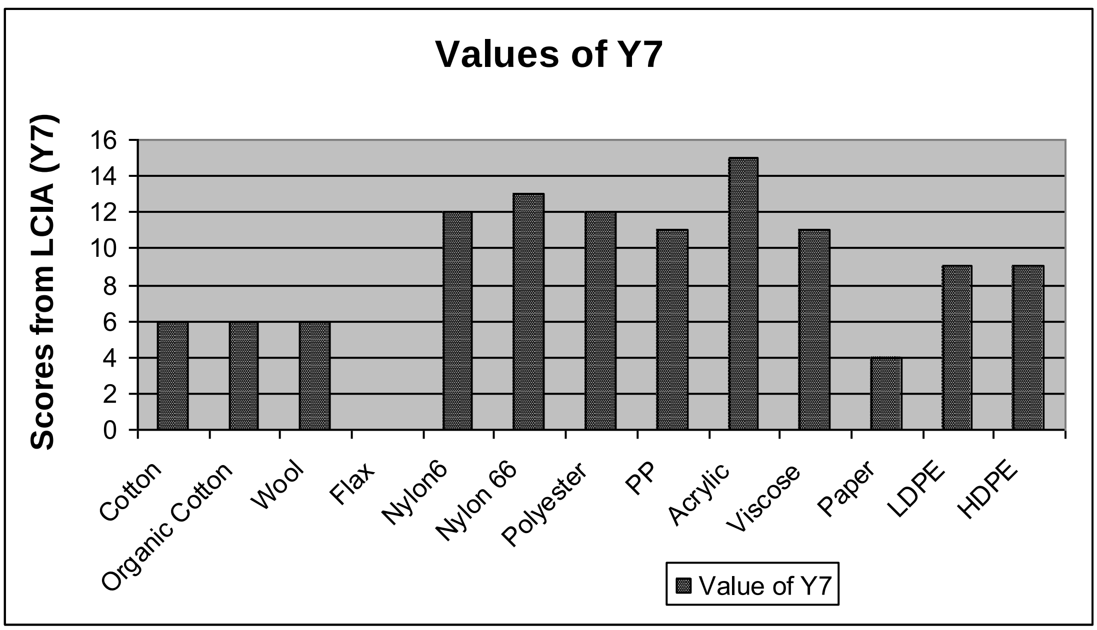


Figure 4-8 Values of LCIA indicators from fibre/raw material production

As explained earlier, the value of Y_7 is the result of life cycle impact categories derived from three important factors considered for fibres and other raw materials production – the energy needs, the water requirements and the CO_2 emissions that led to the fibre stage. This is the score derived from LCA software pertaining to the extent of damage created by the production process of each fibre to human health, eco system quality and resources, where certain issues such as recyclability and biodegradability, the positive effects of plants and trees on off-set global warming are not considered in the currently available LCA models. However, the resultant EI developed from this model is the result of all the factors duly included. The results of the Y_7 and EI values of different fibres and other raw materials are depicted in Fig.4-8 and Fig.4-9. The interpretation of both Y_7 and EI values are the same, i.e. the higher the value, the greater the impact the fibres have on the environment.

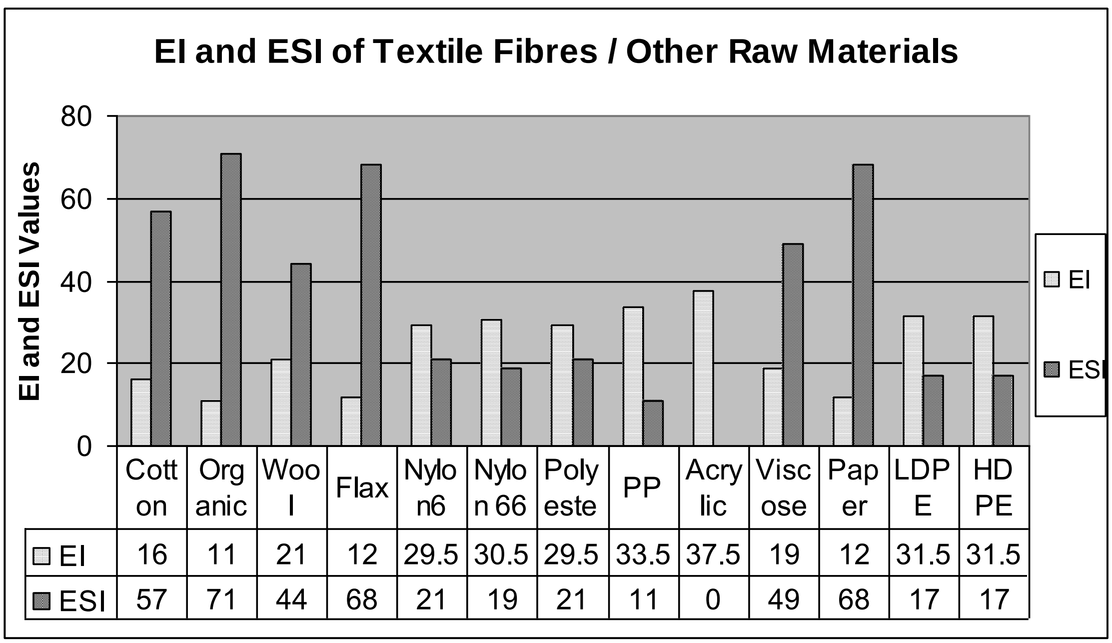


Figure 4-9 EI and ESI values of various textile fibres/raw materials of shopping bags

Fig.4-8 shows that according to the Y_7 values, flax followed by organic cotton, conventional cotton and wool have a lower impact on the environment and acrylic has a greater impact. The EI values in Fig.4-9 reveal that organic cotton is the fibre which has the lowest impact and acrylic has the greatest impact on the environment.

Conventional cotton consumes huge amounts of water as well as fertilisers and pesticides, a certain amount of energy and also emits a considerable amount of CO_2 during production. However, it benefits humanity by producing a large amount of oxygen through photosynthesis. It exerts a medium effect on species extinction and life expectancy and gains an EI value of 16 and Y_7 value of 6.

As regards organic cotton, though it consumes the same amount of water and energy as conventional cotton, it emits less CO_2 and does not require pesticides and fertilizers to enhance its growth. All the other factors considered for determining EI are almost the same as conventional cotton. Because it possesses certain additional qualities over conventional cotton (such as lower energy needs and CO_2 emissions), organic cotton scores better than all the fibres under consideration and gains an EI of 11 (which tops all the fibres under consideration in terms of lower environmental impact) and an Y_7 value of 6 (which is similar to conventional cotton and wool).

Flax consumes less energy than cotton and all other fibres under consideration, and also needs less water than cotton; hence its EI results are better than cotton, and gains an Y_7 value of 0 (which means that it tops all the fibres as far as Y_7 is concerned) and an EI value of 12.

Viscose gained an Y_7 value of 11 and an EI value of 19. Even though it requires less water than conventional cotton and scores as well as other natural fibres in terms of using renewable resources and biodegradability, factors like damages to human health, ecosystem quality and resources are greater during the production process of viscose. In addition, the CO_2 absorption capacity of viscose is less than that of plants according to the scoring system followed in this model. For these reasons, the EI value of viscose is greater than that of both cotton and flax.

Wool scored better than cotton for most of the factors including recyclability, due to the scores earned under the factors like CO_2 emissions and usage of pesticides; it gained an EI value of 21 and an Y_7 value of 6. Although wool scored a similar Y_7 value, its EI value is higher than organic and conventional cotton, and this is mainly due to the absence of CO_2 absorption.

Considering other raw materials for the production of shopping bags such as paper, LDPE and HDPE, paper scores far ahead of its counterparts. It occupies an equal position with LDPE and HDPE and is placed second to organic cotton, owing to its lower environmental impact created in the categories under discussion in this study. LDPE and HDPE registered equal scores and their position lies between PP and nylon 66.

With regard to synthetic fibres like nylon6, 66, polyester, polypropylene and acrylic, (also LDPE and HDPE), because of their non-biodegradability, utilisation of non-renewable resources and large CO_2 emissions, they are not as good as fibres made of biodegradable materials derived from natural renewable resources. Although at times they prevail over natural fibres in certain areas, the negative qualities earn high EI scores, such as 29.5 for nylon 6 and polyester, 30.5 for nylon 66, 33.5 for polypropylene, 31.5 for LDPE, HDPE and 37.5 for acrylic. These scores imply a very high environmental impact. In spite of requiring smaller amounts of water, their higher energy needs and CO_2 emissions result in higher Y_7 values.

4.6.2 Ecological Sustainability Index of different textile fibres and other raw materials

The objective of this research revolves around the concept of ecological sustainability giving due consideration to the factors which determine the ecological sustainability of any fibres/raw materials used for shopping bag production. The scoring system created consists of a comprehensive measure of many factors, which reflect the position of various textile fibres and other raw materials in terms of ecological sustainability. Fig.4-9 gives information about the Ecological Sustainability Index (ESI) derived for each fibre from EI values using equation (2). Both EI and ESI values of all ten fibres and other raw materials under discussion are plotted in Fig.4-9.

In terms of ecological sustainability, the majority of synthetic fibres are less preferred because of the consideration given to certain factors; similarly, while considering the water requirements of different fibres, these fibres are more preferred than natural fibres/raw materials like cotton and paper. There are certain special features as well as certain negative aspects associated with each fibre/raw material. One needs an accurate balance in weighing all factors to examine the position of each fibre/ raw material and the relative position of the fibres/raw materials. The work done in this study aims to act as an accurate balance to determine the ecological sustainability of each fibre/raw material and derive its ecological sustainability index.

The interpretation of ESI is the reverse of the interpretation of EI and can be understood from Eq.2. The higher the ESI value, the more sustainable the environment is. The resultant ESI out of this model is a relative ranking value of a fibre /raw material with the consideration of almost all the factors contributing to ecological sustainability.

The term “ecological sustainability” is well suited to natural fibres/ raw materials which are produced from renewable resources and bring positive effect to living organisms on earth, as demonstrated through so many centuries of human history.

From the values of ESI plotted in Fig. 4-9, organic cotton is most sustainable and acrylic is the least sustainable fibre. Other fibres fall in between these two.

Natural fibres and other raw materials such as conventional cotton, organic cotton, paper, flax and wool score better than the synthetic fibres. Among these, organic cotton tops the list of chosen fibres with an ESI of 71 followed by paper and flax, which gained an equal ESI of 68. Conventional cotton and viscose gained ESIs of 57 and 49 respectively. Viscose is ranked between natural and synthetic fibres. Wool gained an ESI of 44.

Regarding synthetic fibres like nylon6, 66, polyester, polypropylene, LDPE, HDPE and acrylic, they are not as ecologically sustainable as fibres made of biodegradable materials and derived from natural, renewable resources. They earned low ecological sustainable index values such as 17 for LDPE, HDPE, 19 for Nylon 66, 21 for nylon 66 and polyester, 11 for polypropylene and 0 for acrylic; values which imply poor ecological sustainability. In this category, nylon 6 and polyester seem to be better, followed by nylon 66.

4.6.3 Sensitivity analysis

A sensitivity analysis was made to check the robustness of the developed model by changing the weights of the weighing coefficients shown in Equation 1 to reveal the importance of certain individual factors. The default value of EI is the one represented in Fig. 4-9 by assuming all weighing co-efficients (α_1 - α_7) as equal (equal weights).

Sensitivity analysis was performed in two cases, which are described below.

Case 1:

Of all the various factors studied in this research work, one of the prime factors is the amount of oxygen released back to the atmosphere, as a result of photosynthesis. This has a positive effect on humanity, without which it is difficult for the human race to continue surviving on earth. Keeping this in mind, a maximum weightage, say 50%, is assumed for this individual factor (Y_1) and the remaining 50% significance is shared between all the other factors. In light of this assumption, the EI values according to Eq.1 are recalculated, with the condition of $\Sigma\alpha_j = 1, 0 \leq \alpha_j \leq 1$. The resultant EI is termed EI-1 and compared with the EI default (given in Fig.4-9) and is depicted in Fig.4-10.

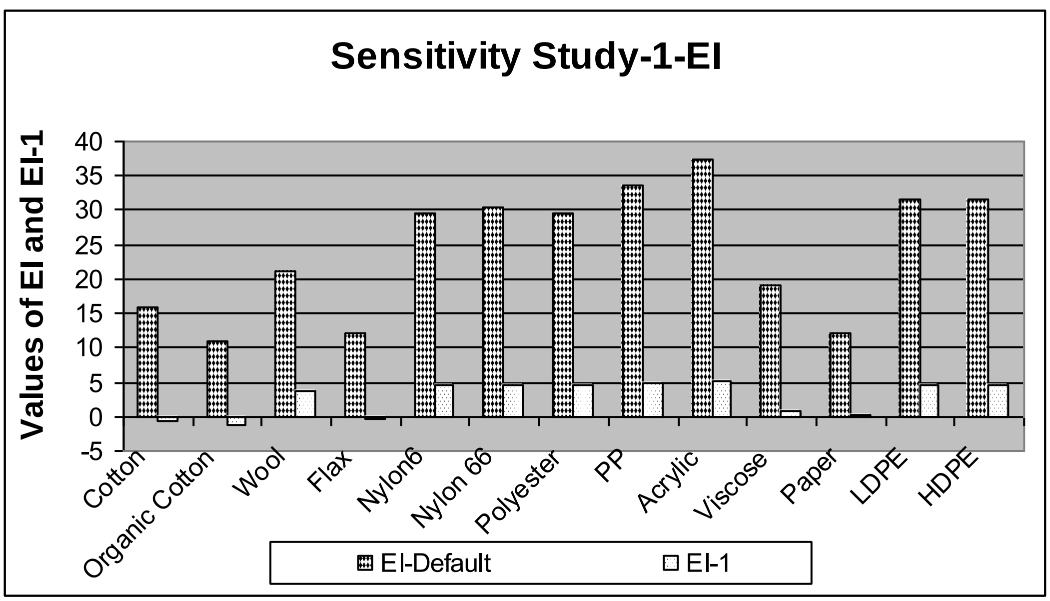


Figure 4-10 Sensitivity Study – Case 1- EI Values

Fig. 4-10 shows that EI-1 results in negative values for conventional cotton, organic cotton and flax, which imply environmental gains and are clearly the result of the photosynthesis effect. Though the same effect is also applicable to viscose and paper, they still are on the positive EI side only due to lower CO_2 absorption than cotton and flax fibres. All the fibres obtained from trees and plants have lower EI values in this case study owing to the benefits and values they extend to humanity.

ESI values are also recalculated (ESI-1) for the resultant EI-1 values and they are compared with the ESI default (from Fig.4-9) and are plotted in Fig.4-11. Referring to Fig.4-11, it is clear that the ESI-1 values are different for fibres and other raw materials and hence the position of different fibres and other raw materials in terms of ecological sustainability. For instance, conventional cotton occupies the position immediately below flax and paper in the case of ESI default. But in this sensitivity study, conventional cotton outscores flax and paper and all of the other fibres assume similar positions in terms of ESI.

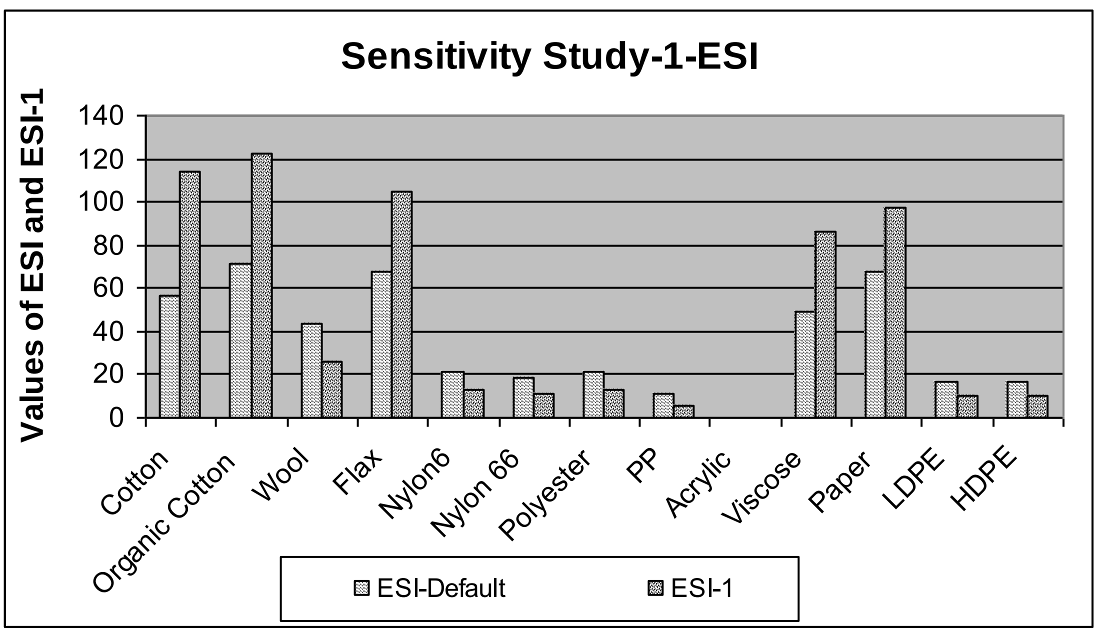


Figure 4-11 Sensitivity Study – Case 1- ESI Values

Case 2:

In the second case study, the maximum significance was given to LCIA impact categories, derived from energy, water and CO_2 emissions. Similar to case 1, the factor (Y_7) assumed 50% importance and the remaining 50% are shared between all the other factors. With these assumptions, EI values were recalculated for various fibres as per Eq.1 with the condition $\Sigma\alpha_j = 1$, $0 \leq \alpha_j \leq 1$. Results of this case (EI-2) are compared with the EI default (from Fig.4-9) and are represented in Fig.4-12.

According to Fig.4-12, flax has the lowest environmental impact and acrylic exerts greater environmental impact after the recalculation of EI with the assumption of greater importance to life cycle impact categories. It is quite an obvious result, which can be well understood from Fig.4-8.

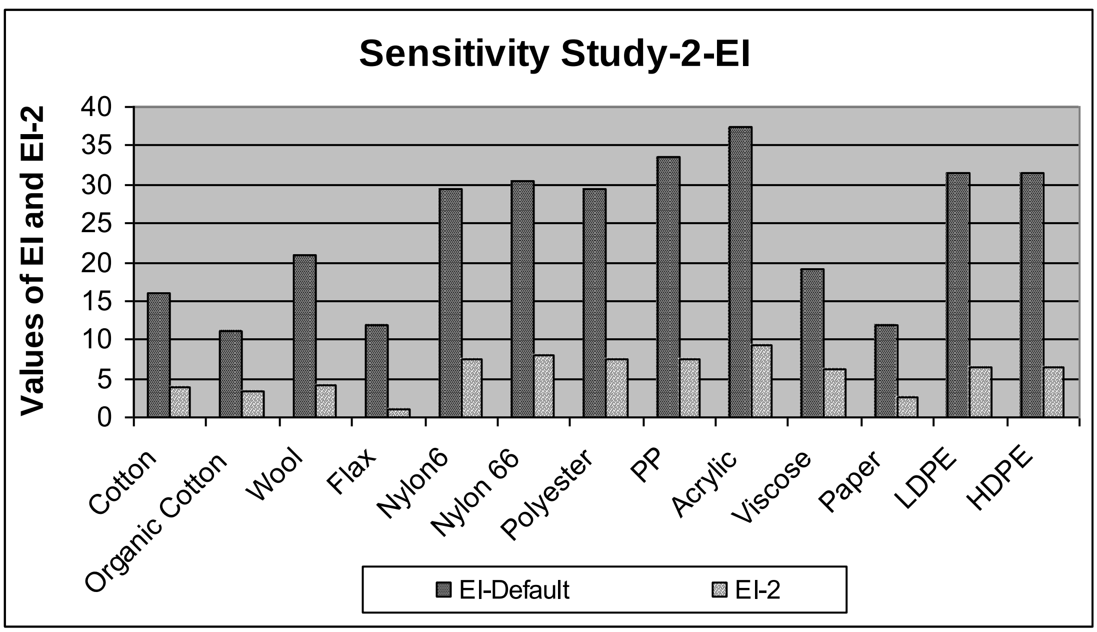


Figure 4-12 Sensitivity Study – Case 2- EI Values

ESI values are also recalculated (ESI-2) for the resultant EI-2 values. They are compared with the ESI default (from Fig.4-9) and are plotted in Fig.4-13. In this case study, one can see the phase shift in the position of different fibres in terms of their ESI values. For instance, during ESI default calculation, acrylic seems to be less ecologically sustainable and organic cotton appears to be more ecologically sustainable. Paper assumes a better position than even organic cotton. But when the importance is shifted to life cycle impact categories, flax tops all the fibres and seems to be more ecologically sustainable. Polypropylene assumes a better position than polyester, nylon 6 and 66 fibres. Also LDPE and HDPE top all their counterparts in the synthetic categories in this sensitivity study.

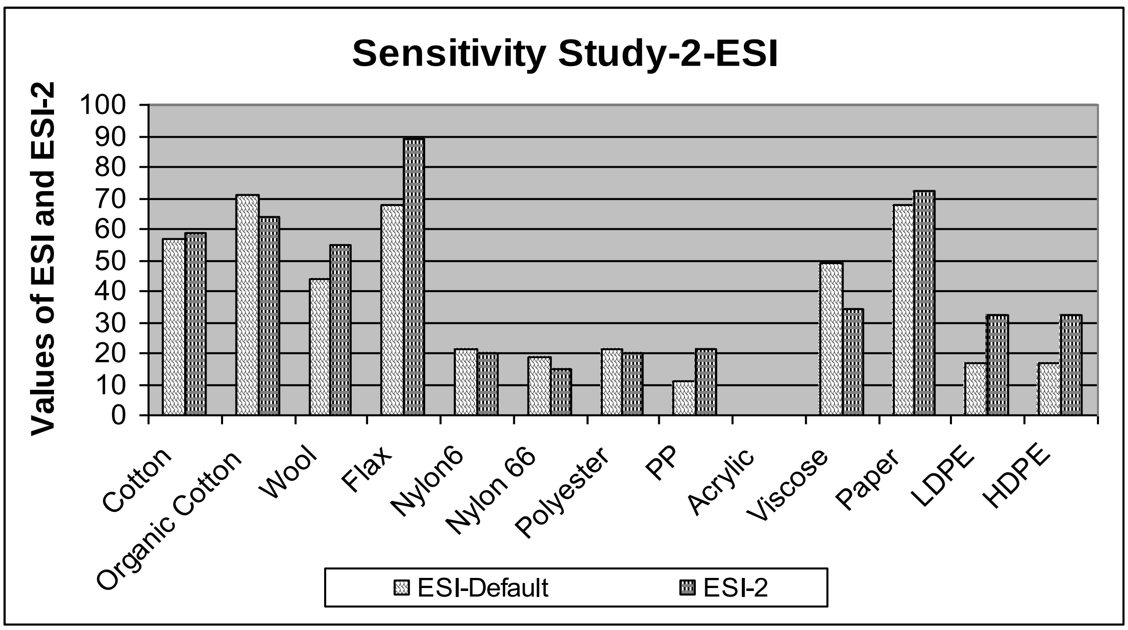


Figure 4-13 Sensitivity Study – Case 2- ESI Values

The developed model is very flexible and it goes very well with different sets of data as well as factors apart from the ones considered in this study. One can use this model to study the environmental impact and ESI of any fibre with a completely different scoring system/method, since the scoring system used in this model is essentially subjective. This is admittedly a limitation of the proposed model, but must be offset against models' considerable flexibility.

The sensitivity study shows that the environmental impact and ranking of different fibres and other raw materials according to ecological sustainability can be different for different considerations, depending on the importance given to individual factors, which are often subject to different views and arguments of various stakeholders.

This model provides a simple and effective means to quantify the effects of different fibres and other raw materials on the environment and calculate their environmental impact and ecological sustainability. Further, the scoring systems are quite arbitrary and can be further rationalized through an open discussion among various textile/other raw material sectors and institutions (Muthu et al., 2012d).

This research has attempted to create a model to develop an index for various textile fibres and other raw materials in terms of ecological sustainability during the production phase before conversion into useful fibres and enhance our knowledge of factors contributing to the ecological sustainability of each textile fibres and other raw materials during their production phase. This attempt contributes to knowledge about various textile fibres and other raw materials in terms of their ecological sustainability.

The model developed in this study results in an Environmental Impact Index (EI) and Ecological Sustainability Index (ESI) of ten chosen fibres and other raw materials such as paper, LDPE and HDPE. These two indices were derived from a scoring system developed from the consideration of factors such as amount of oxygen produced/carbon dioxide absorbed, consequently contributing to off-set global warming during the production phase of a fibre, utilisation of renewable resources, land use, usage of fertilisers and pesticides, fibre recyclability, and biodegradability of chosen fibres were considered (values for these factors were referred from facts and figures supplemented by various references). The scoring system also included certain life cycle impact categories derived from the amount of energy used, quantity of water utilised, and amount of green house gases emitted (the values for these factors were referred from secondary data sources).

From the results of the developed model, organic cotton seems to have the least environmental impact and is a more sustainable fibre with an EI of 11 and ESI of 71, followed by paper and flax with an equal EI of 12 and ESI of 68, conventional cotton and viscose with EIs of 16 and 19 and ESIs of 57 and 49 respectively, polyester with an EI of 29.5 and an ESI of 21 and so on. Acrylic is the least preferred fibre in terms of environmental impact and ecological sustainability.

The position of organic cotton and acrylic in this developed model is the cumulative result of the consideration of various factors listed above, which develop a picture of environmental impact and ecological sustainability. Considering certain common and important factors for the production of organic cotton and acrylic, organic cotton is derived from a renewable resource, is a biodegradable fibre, consumes lesser energy for manufacturing and emits lesser CO_2, and subsequently creates less damage to human health, ecosystem quality and resources. All these factors are reversed for acrylic and hence it has a greater environmental impact and is the least sustainable fibre amongst its rivals under consideration.

However, the results are derived on the basis of the index scores given to each fibre/raw material and the scoring system that was consequently developed using secondary data for LCI. The LCIA results provided by the software also rest on certain hypotheses and assumptions.

4.7 Conclusions

This chapter discussed the life cycle inventory details of ten textile fibres and other raw materials used for shopping bag production to test the first research question. Also the details of a unique model developed to quantify the environmental impact and ecological sustainability of textile fibres and other raw materials used for shopping bags production were discussed in detail. EI and ESI values quantified for different raw materials were reported along with the results of sensitivity study. The following chapter will discuss the life cycle inventory and other relevant details of the production phase of various shopping bags, which relate to research question 2 stated in Chapter 3.

Chapter 5 Life Cycle Inventory Analysis, Eco-Damage and Carbon Footprint Assessments, Manual LCA Calculations of Production Stage of Grocery (Shopping) Bags

5.1. Introduction

This chapter deals with the life cycle inventory analysis for the production processes of various shopping bags used for grocery purposes, i.e. plastic (LDPE and HDPE), paper (Kraft), polypropylene nonwoven bags and cotton woven bags. Life cycle inventory details were collected for these bags from secondary data sources. Also this chapter revolves around the collection of primary data for production processes for nonwoven shopping bags made out of polypropylene by means of a life cycle audit conducted in a factory manufacturing nonwoven bags. This chapter serves as a base to collect the essential details in terms of life cycle inventory needed for testing research question 3 given in Chapter 3.

This chapter also discusses the study of eco-damage and carbon footprint assessments of nonwoven bag shopping bags from primary data obtained from the life cycle audit. These assessments were performed with the aid of one of the leading commercial LCA packages, SIMAPRO version 7.2. Apart from the software-generated results, this chapter also reports the LCA values of shopping bags, which were assessed using secondary data sources calculated manually using familiar LCA equations and characterization and normalization values pertaining to China (using Chinese factors, i.e.

values of impact categories pertaining to Chinese consumers). All these assessments and analyses of different shopping bags were done from the cradle to gate stage.

5.2. Life cycle assessment of shopping bags

There are different types of shopping bags available to cater to the various shopping needs of people. A variety of raw materials and technologies are employed to manufacture them, of which the most popular are plastic, paper, nonwoven and woven bags. Regarding reusable bags, nonwoven and woven bags top the list.

Most products have an impact on the planet, so quantifying their impact is crucial to reducing it. Of the many techniques used to study the eco-impact of a product, life cycle assessment (LCA) is one of the most widely used and popular. LCA examines the product from the initial (cradle stage) to the final stage (grave stage), covering the entire life cycle, and also evaluates the product in terms of the eco-impact during its life time.

Shopping bags, being perceived as a symbol of a throw-away society, require LCA to assess their eco-impacts. A large number of studies have been conducted to investigate the LCA of various shopping bags (Ellis et al., 2005; Chaffee and Yaros, 2007; Carrefour, 2004; Ecobilan, 2008; FRIDGE; www.sustainability-ed.org; Franklin Associates, 1990; GUA, 2005; Los Angeles County Department of Public Works, 2007; Nolan ITU et al., 2002; ExcelPlas Australia et al., 2004; James and Grant, 2005; The ULS Report, 2008; McGrath; Muthu et al., 2009 ; Muthu et al., 2010b). Most of the studies focused on plastic and paper bags, but very little work has been done on nonwoven and woven bags. Fig.5-1 outlines the manufacturing sequence for shopping bags and the corresponding life cycle. For any type of shopping bag, the first three steps vary significantly in terms of variables such as raw materials and processing technology (shown in dotted lines inside Figure 5-1). The raw material stage is covered in the previous chapter. The production processes of various shopping bags are covered in this chapter and the consequent phases are dealt in the forthcoming chapters.

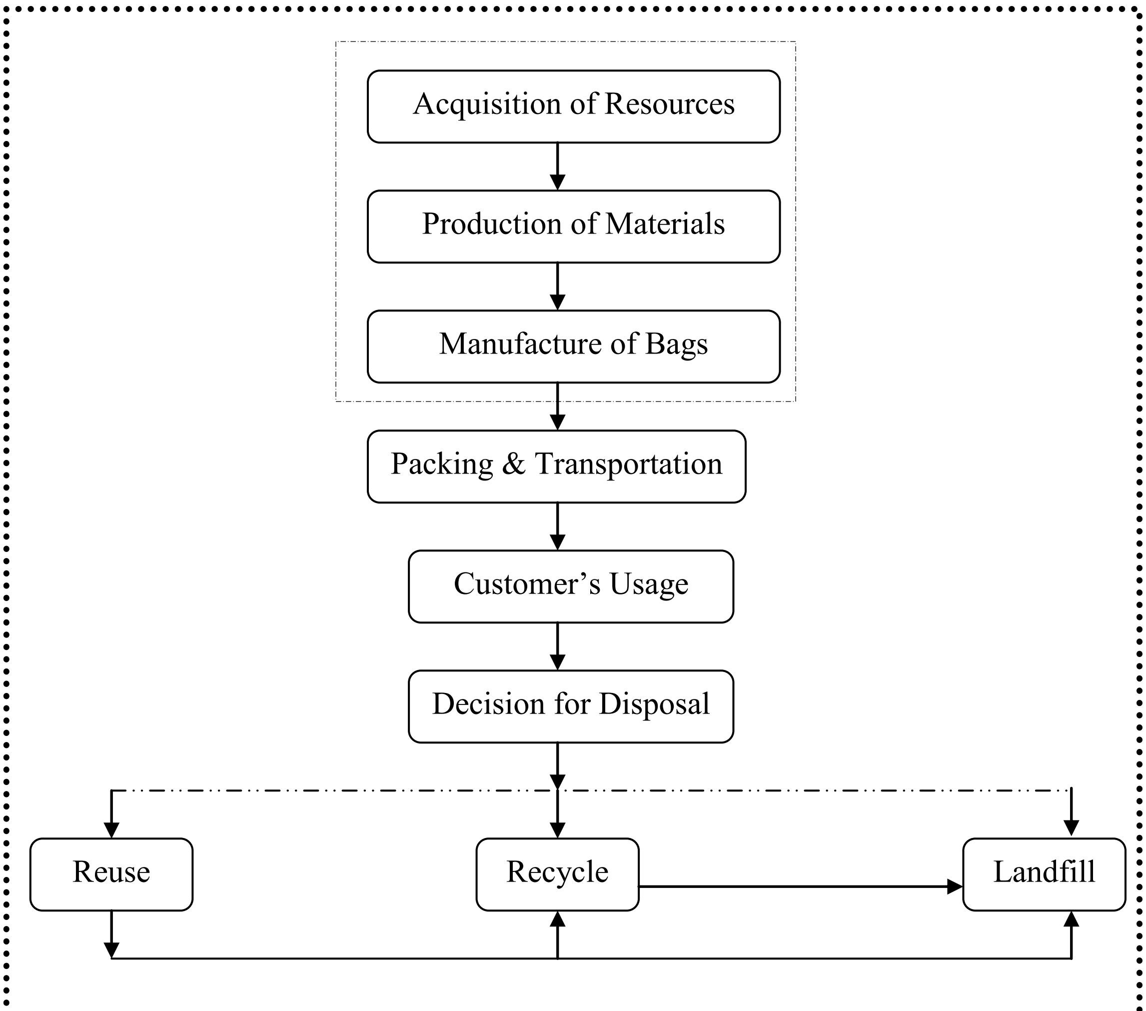


Figure 5-1 General outline of Life Cycle Assessment of shopping bags

5.3 Life cycle inventory of shopping bags

Plastic (LDPE and HDPE), paper (Kraft paper), polypropylene nonwoven bags and cotton woven bags are considered for the present study. Plastic and paper bags, which come under the single use category, are discussed first, followed by the reusable bag category. The initial step of this study is the collection of the secondary data for LCI which was obtained from the final report prepared for Environment Australia in 2002 (Nolan ITU et al., 2002).The same data were also reported in an updated version of this study published in 2004 (ExcelPlas Australia et al., 2004).Data pertaining to this study focuses on key issues such as material consumption, energy needed for manufacturing process and green house gas emissions.

The scope and boundaries of this study are limited to the LCI obtained from the available data. The functional unit of this study was derived from the literature of relevance (Nolan ITU et al., 2002; ExcelPlas Australia et al., 2004; James and Grant, 2005; Muthu et al., 2010b; Muthu et al., a; Muthu et al., 2012a) (i.e. sufficient capacity for a household consuming approximately 70 grocery items which were carried away from a supermarket in shopping bags every week for 52 weeks).

Plastic and paper bags

Some previous studies (Ecobilan, 2008; FRIDGE; www.sustainability-ed.org; Franklin Associates, 1990) dealt with LCA comparison of plastic and paper shopping bags and raised a number of issues and concerns. Different conclusions were drawn from the above studies, which are discussed below:

1. The study by Franklin Associates, which compared the impact of single-use paper and polyethylene bags in the USA, assumed a ratio of 2 plastic to 1 paper bag and concluded that plastic carry bags had lower environmental impacts and used less

energy at current recycling rates (Muthu et al., 2009; www.sustainability-ed.org; Franklin Associates, 1990).

2. From the study carried out by Bentley West Management Consultants, South Africa, contradictory results were presented. Also it was advised to conduct a streamlined LCA study to conclude which bag is more environmentally friendly in the South African context (FRIDGE).
3. Ecobilan study concluded that except for the production of waste and risks linked to discarding, the environmental advantages of paper carrier bags are primarily related to energy consumption: low consumption of non renewable energy, low contribution to the greenhouse effect and limited photo-oxidant chemical formation in comparison to plastic carrier bags (Ecobilan, 2008).

These studies are some of the important ones for dealing with only plastic and paper bags. There are many studies that have investigated the environmental impacts of various shopping bags and also included plastic and paper bags (Carrefour, 2004; Los Angeles County Department of Public Works, 2007; Nolan ITU et al., 2002; ExcelPlas Australia et al., 2004; James and Grant, 2005; Dilli, 2007). In some of these studies (Los Angeles County Department of Public Works, 2007; Nolan ITU et al., 2002; ExcelPlas Australia et al., 2004; James and Grant, 2005; Dilli, 2007), an end-of-life assumption was included to model the LCA of shopping bags to exemplify their cradle-to-grave assessment. However, to obtain a better understanding of the eco-impact of various shopping bags, the cradle-to-grave study must employ real data of recycling/reuse/landfill options, derived from the consumers of shopping bags. This process is discussed in Chapter 6.

The energy and pollutants data for plastic and paper bags for the functional unit considered was taken from previous studies (Nolan ITU et al., 2002; ExcelPlas Australia et al., 2004) as tabulated in Table 5.1. Table 5.1 shows that plastic bags consume significantly less energy than paper bags do. This is also applicable to green house gas emissions.

Alternative	Weight/bag	Bags/year	Material Consumption	GHG(CO_2 emissions)	Primary Energy
Plastic bag - HDPE	6.0 gms.	520	3.12 kgs.	6.1 kgs.	210 MJ
Plastic bag - LDPE	18.1 gms.	650	11.77 kgs.	29.8 kgs.	957 MJ
Paper bag	42.6 gms.	520	22.15 kgs.	11.8 kgs.	721 MJ

Table 5-1 Life Cycle Inventory data of plastic and paper bags (results rounded-off) (Nolan ITU et al., 2002; ExcelPlas Australia et al., 2004)

Nonwoven and woven bags

The energy and pollutants data for nonwoven and woven bags for the functional unit considered were taken from previous studies (Nolan ITU et al., 2002; ExcelPlas Australia et al., 2004) as tabulated in Table 5-2. Table 5-2 shows the differences between energy and pollutants data for the nonwoven and woven bags. Nonwoven bags consumed less materials and primary energy and Green House Gas (GHG) emissions compared to woven cotton bags for the identical functional unit assumed for this study.

Alternative	Weight/bag	Bags/year	Material consumption	GHG(CO_2 emissions)	Primary energy
PP fibre “Green bag”	65.6 gms.	4.15	272.24 gms.	1.96 kgs	46.3 MJ

Woven cotton bag	125.4 gms.	9.1	1.14 kgs.	2.52 kgs.	160.0 MJ

Table 5-2 Life Cycle Inventory data of nonwoven and woven bags (Nolan ITU et al., 2002; ExcelPlas Australia et al., 2004)

Table 5-3 lists the life cycle inventory data recalculated for material consumption, GHG emissions and primary energy to produce 1 unit of bag from the same secondary data sources.

Alternative	Weight/bag	Material consumption	Green House Gas emissions (CO_2 eq.)	Primary energy
Plastic bag (HDPE)	6.0 gms.	6.0 gms.	11.6 gms.	0.40 MJ (0.11 Kwh)
Paper bag (Kraft paper)	42.6 gms.	42.6 gms.	22.7 gms.	1.40 MJ (0.39 Kwh)
Boutique plastic (LDPE)	18.1 gms.	18.1 gms.	45.8 gms.	1.47 MJ (0.41 Kwh)
Woven cotton bag	125.4 gms.	125.4 gms.	277.0 gms.	17.58 MJ (4.88 Kwh)
PP fibre nonwoven bag	65.6 gms.	65.6 gms.	472.0 gms.	11.15 MJ (3.1 Kwh)

Table 5-3 LCI of various shopping bags for 1 bag (Nolan ITU et al., 2002; ExcelPlas Australia et al., 2004)

5.4. Life cycle audit

Apart from the data from secondary data sources shown above, this research also reports the method of conducting a life cycle audit in a shopping bag factory to collect the primary data, to conduct the LCA study to examine the environmental performance of the shopping bags under consideration and also to locate the hot-spots in the production process of shopping bags.

A comprehensive life cycle audit was conducted in a factory manufacturing nonwoven shopping bags for a week to analyse the inventory details of each section of the nonwoven bags manufacturing process. The study was conducted in one of the leading nonwoven manufacturing companies in China, "National Bridge Industrial (Shenzhen) Co., Ltd", situated in Shenzhen, China. This company has two manufacturing set-ups. One set-up produces nonwoven fabrics which are transported to another set-up, where the garment manufacturing processes take place, such as spreading, cutting, screen printing, sewing and packaging. This factory has a patented technology to replace sewing technology. They use thermal technology to join the cut pieces of fabrics to produce a shopping bag. According to the request of customers, they either choose the cutting technology or the thermal technology method to produce nonwoven shopping bags. Details pertaining to life cycle audit conducted are given in Appendix 1.

Details of the life cycle assessment study are presented in this chapter. This study aims to compare the life cycle impacts of two products selected for this study, produced out of two major technologies used to manufacture shopping bags (thread sewing and thermal attachment). Also this study discussed the hot-spots in the production process of both types of bags considered for this study.

The manufacturing process for these bags begins with raw material preparation, i.e. preparation of polypropylene chips, followed by spun bonding process. This is followed by the other processes such as cutting, screen printing, sewing and packaging.

In this lengthy process, sewing is one of the widely used techniques utilised to join the separated (cut) parts with stitches to form a useful product. For shopping bags, at this stage, two sides of a bag are sewn together and also the handles are attached to the body of the bag. The same operation can be replaced by a thermal technology, where very high temperature is used as a means to achieve this operation performed by conventional sewing. Since it is a technology patented by the industry, where the field study took place, details of this technology cannot be disclosed here in accordance with the request of the industrial partners. This research work describes the environmental performance assessment of nonwoven polypropylene shopping bags produced out of the two methodologies discussed above.

As stated earlier, a large number of studies have been conducted in the area of environmental performance of shopping bags to investigate their Life Cycle Assessment (LCA) (Ellis et al.,2005; Chaffee and Yaros, 2007; Carrefour, 2004; Ecobilan, 2008; FRIDGE; www.sustainability-ed.org; Franklin Associates, 1990; GUA, 2005; Los Angeles County Department of Public Works, 2007; Nolan ITU et al., 2002; ExcelPlas Australia et al., 2004; James and Grant, 2005; The ULS Report, 2008; McGrath; Muthu et al., 2009 ; Muthu et al., 2010b). However, most of the studies focused on plastic and paper bags and very little work has been done on nonwoven and woven bags compared to plastic and paper bags. Even among the few studies published about nonwoven bags, a comprehensive life cycle inventory is not available on nonwoven bags exclusively and there is a dearth of articles analysing the hot-spots in the production processes of nonwoven bags. Being the first work in this kind, this present study outlines the detailed life cycle inventory of nonwoven shopping bags manufacturing process and also explains the results. The following product types are considered for this LCA study and their processing sequence is explained in Figs.5.2-5.3.

1. **Product A- Sewn bag**, (Fabric weight: 100g/m^2; Size: 43(L)*38(H)*24(D) cm ;)

2. **Product B- Thermo bonded with Cutting**

(Fabric weight: 75g/m^2; Size: 36(L)*42.5(H)*19.5(D) cm ;)

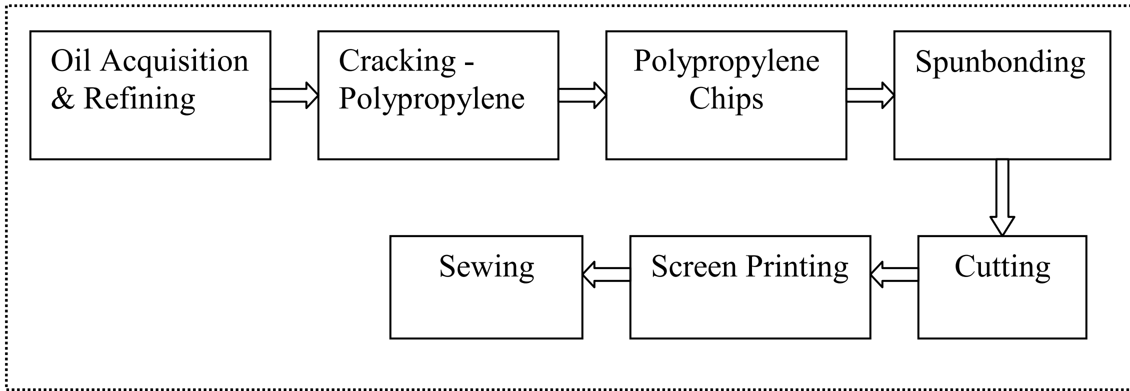


Figure 5-2 Manufacturing process of nonwoven bags – Sewing technology- Product A

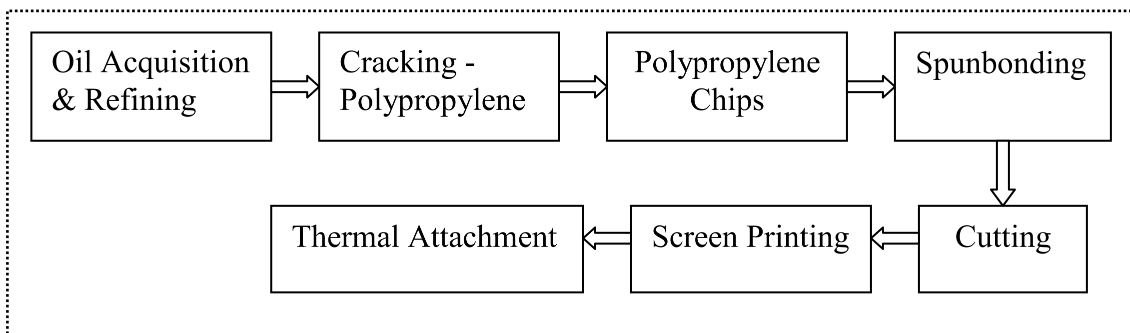


Figure 5-3 Manufacturing process of nonwoven bags – Thermal Attachment- Product B

5.4.1. Life cycle assessment of nonwoven shopping bags - *Goal and scope*

The goals and scope of this study are: a) To review the inventory of inputs and outputs for both different kinds of shopping bags selected for this study; b) The main goal of this study is to identify the hot-spots in the two major techniques of production process of nonwoven shopping bags discussed above from reviewing the environmental impacts of products A and B; c) To compare the environmental impacts of two major technologies of nonwoven bags production by comparing the environmental impacts of the production of 1 Kg of products A and B.

The boundaries of the study can be seen from Fig.5-4. Though this study does not directly report the inventory of PP and master batch, their associated inventory data were taken from the eco-invent dataset library, using SIMAPRO software. Original transportation of PP and master batch from the manufacturing plants to this factory are not included in this study. Final transport of shopping bags to customers is also not considered in this study.

5.4.2. Life cycle inventory

The life cycle inventory (LCI) of both products A and B considered in this study is given in Table 5-4. For both of the products, a transportation distance of 6kms from spun bonding factory and 15 kms for chemicals and other ancillaries for cutting, screen printing process is common. Road transport by means of diesel trucks is applicable to both of the products in this study.

5.4.3. Life cycle impact assessment – Eco-damage & carbon footprint assessments

Environmental Performance assessment was performed with the aid of SIMAPRO 7.2 software from Pre Consultants, Netherlands. A damage-oriented method, Eco-Indicator'99, Hierarchist method of V2.06 version was used to quantify the life cycle impacts. Carbon footprint assessment was also performed with the aid of SIMAPRO 7.2 software. IPCC 2007 GWP V 1.1. method, a successor to the IPCC 2001 method, developed by the Intergovernmental Panel on Climate Change, was utilized to calculate the global warming potential (GWP) for 100 and 20 years (Life Cycle Impact

Assessment; Life Cycle Impact Assessment Methods; Ecoindicator' 99 method; Goedkoop et al., 2000 & 2001; SIMAPRO software; Muthu et al., 2009).

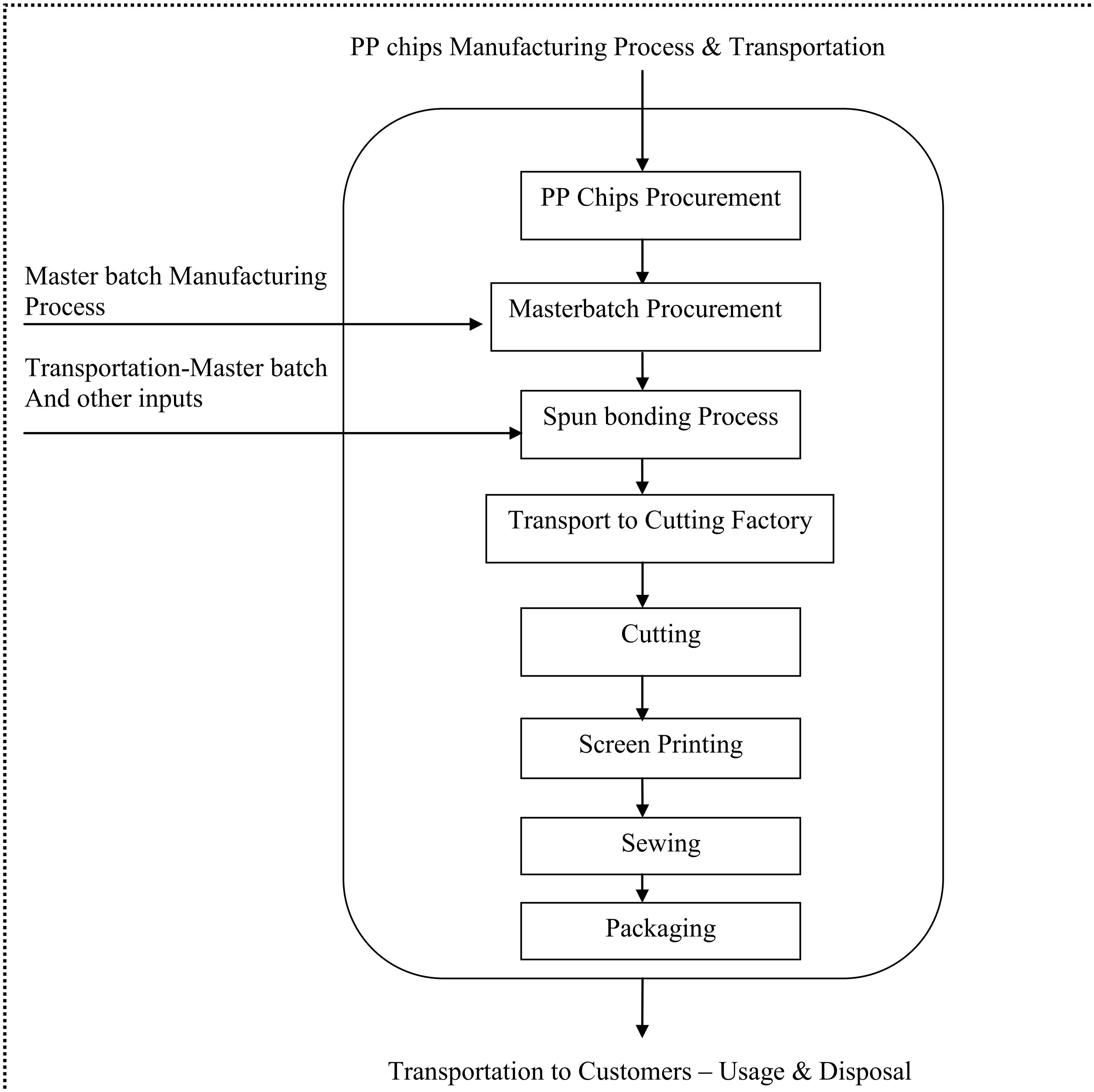


Figure 5-4 Scope and boundaries of the system under study

Life cycle inventory	Product A[1]	Product B[2]
1. Spun-bonding inputs:		
PP chips	82.12 g	64.2 g
Master batch	1.16 g	0.91 g
Electricity		
- Manufacturing	0.0892 Kwh	0.0697 Kwh
- Lighting	0.00163 Kwh	0.00127 Kwh
- Cleaning	0.0002 Kwh	0.00015 Kwh
Water(Cleaning)	1.01 g	0.79 g
NaOH(Cleaning)	0.0021 g	0.0016 g
Paper Tubes	2.97 g	2.32 g
Plastic Sheet (PE)	0.58 g	0.45 g
Outputs:		
Fabrics –standard quality	79.7 g	62.3g
Fabrics in low quality and multi colour ones	2.37 g	1.85 g
Fabrics- waste	3.6 g	2.82 g
2. Cutting inputs:		
Spunbonded fabrics	79.7 g	62.3 g
Electricity	0.00267 Kwh	0.00267 Kwh
Outputs:		
Cut pieces of fabrics	75.4 g	51.67 g
Waste fabrics	0.00426 kg	10.58 g
3. Screen printing inputs:		
Fabrics (PET mesh) for Screen	1.44 grams	0.72 grams
Aluminum for Screen	3.34 inches	1.67 inches
Wood for screen	0.0001 inches	0.00005 inches
PE film	0.3 g	0.2 g
Printing ink	3.3 g	3.73g
Electricity (lighting & fan)	0.0178 Kwh	0.0178 Kwh
Silicone spray	0.16 g	0.16 g
ABS-Cyanoacrylate	0.06 g	0.06 g
Cyclohexanone	3 g	3 g
Autotype Plus 7000 Direct Emulsion	0.4 g	0.4 g
Isophorone	0.65 g	0.65 g
Adhesive	2.5 g	2.5 g
Water(cleaning)	0.63 g	0.63 g
Fluid waste (water)	45.8 g	45.8 g
Solid waste (chemicals & others)	4.17 g	4.17 g
4. Sewing:		
Electricity	0.0081 Kwh	NA
Thread used	0.5 g	NA

5. Thermal Bonding inputs:		
- Electricity	NA	0.0305Kwh
- Fabric waste	NA	NIL
6. Packaging inputs:		
Paper box	8.21 g	8.21 g
Plastic sheet (PE)	0.5 g	0.5 g

Table 5-4 LCI of Products A and B for 1 bag in each category

[1](Weight of 1 bag: 79.2 gms)
[2] (Weight of 1 bag: 55.4 gms)

Comparative assessment of sewing and thermal technologies

A comparative analysis of the two production technologies considered for study is presented in Figs.5-5 - 5-8. For this study, the production processes involved in manufacturing 1 Kg of products A and B are considered.

The results of the co-damage assessment by eco-indicator'99 are presented in the following five steps. Figures 5-5-5-8 explain the various stages of impact assessment. The impacts are characterized into different categories and the extent of damage to the categories is shown in Fig.5-5. Figs.5-6 and 5-7 show the normalized and weighted impact scores. Fig.5-8 explains the single score results of two products under consideration. Carbon footprint assessment results for 20 and 100 years are presented in Tables 5-5 and 5-6.

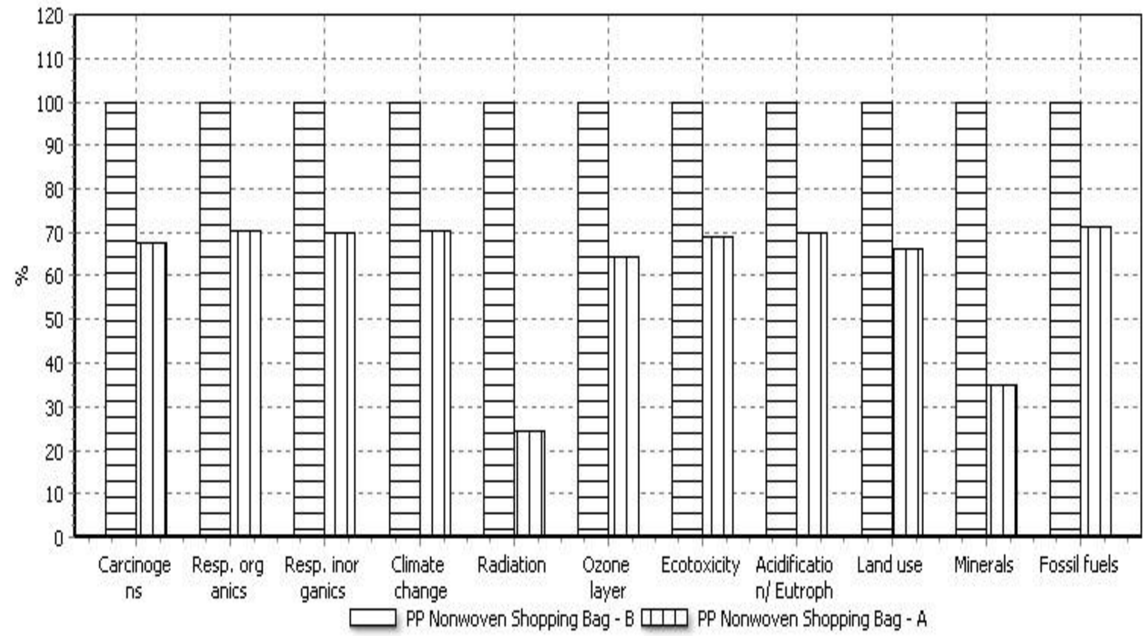


Figure 5-5 Characterisation & damage assessment results

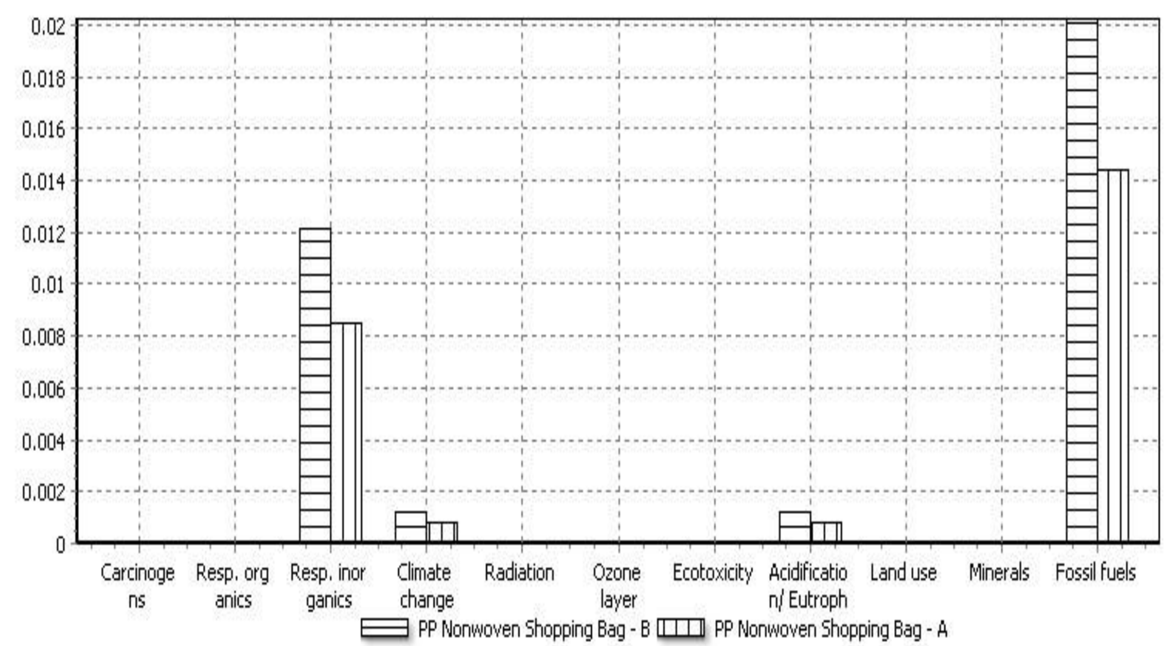


Figure 5-6 Normalisation results

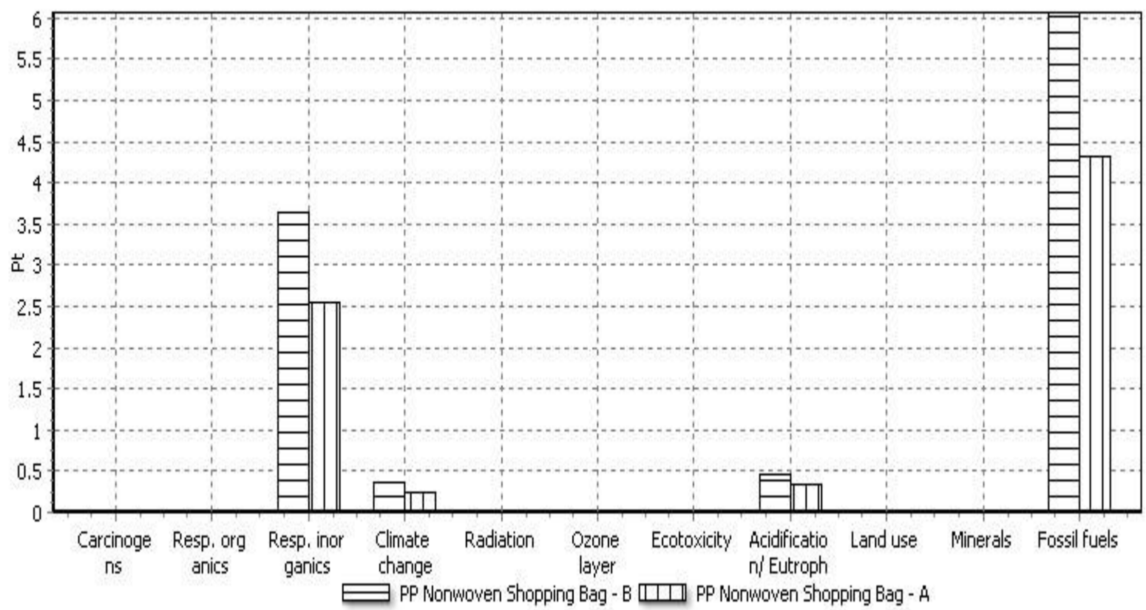


Figure 5-7 Weighting results

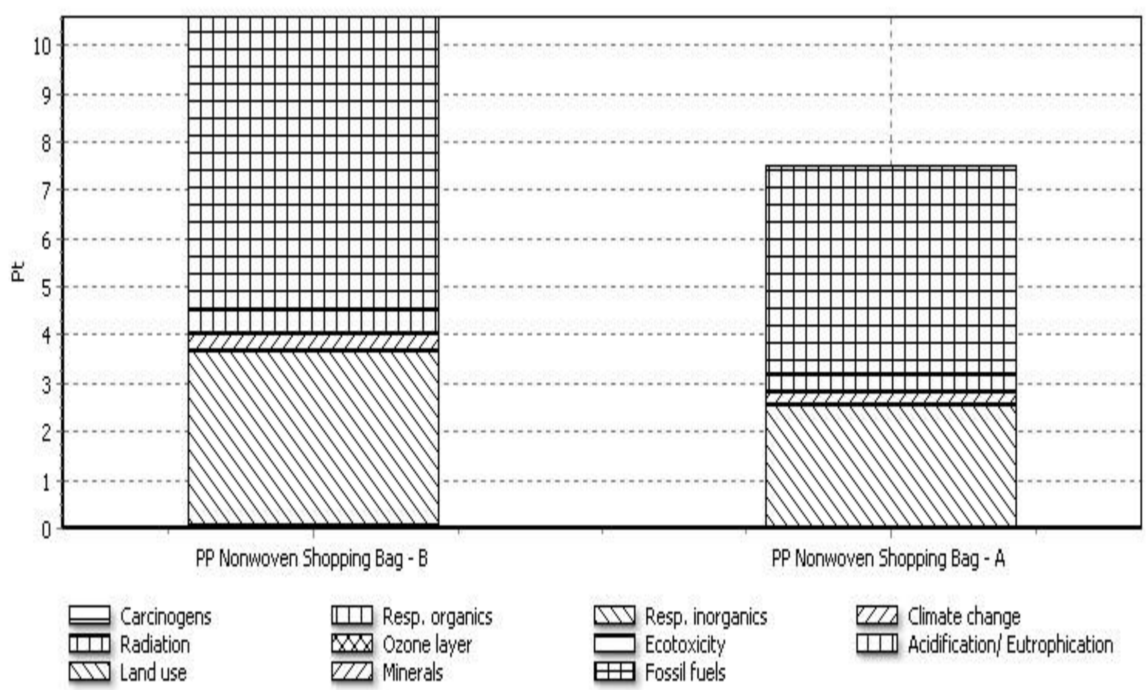


Figure 5-8 Single score results

Impact category	Unit	A	B
IPCC GWP 100a	kg CO_2 eq	60.7	86.3

Table 5-5 Carbon footprint (GWP values) for products A and B (100 years)

Impact category	Unit	A	B
IPCC GWP 20 a	kg CO_2 eq	62.5	88.6

Table 5-6 Carbon footprint (GWP values) for products A and B (20 Years)

Hot-spots in the production processes

The hot-spots in the production processes of the two technologies under consideration are reviewed by studying the environmental impacts made by the production processes involved in manufacturing 1 Kg of products A and B. The hot-spots analysis from the process contribution graphs of products A and B in the Eco-Indicator'99 method are shown in Figs. 5-9 – 5-10. Carbon footprint for 20 and 100 years for both products A and B are shown in Figs.5-11 – 5-14.

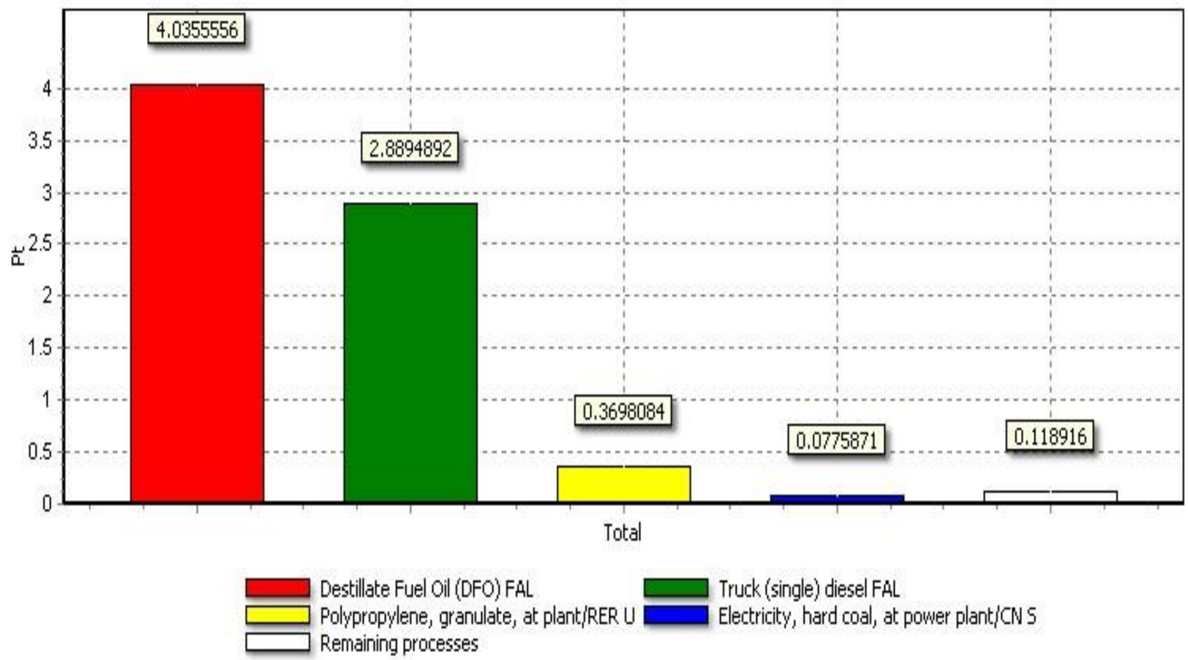


Figure 5-9 Hot-spots in the manufacturing process of Product A (Eco-indicator'99 method) (Cut-off value: 1%)

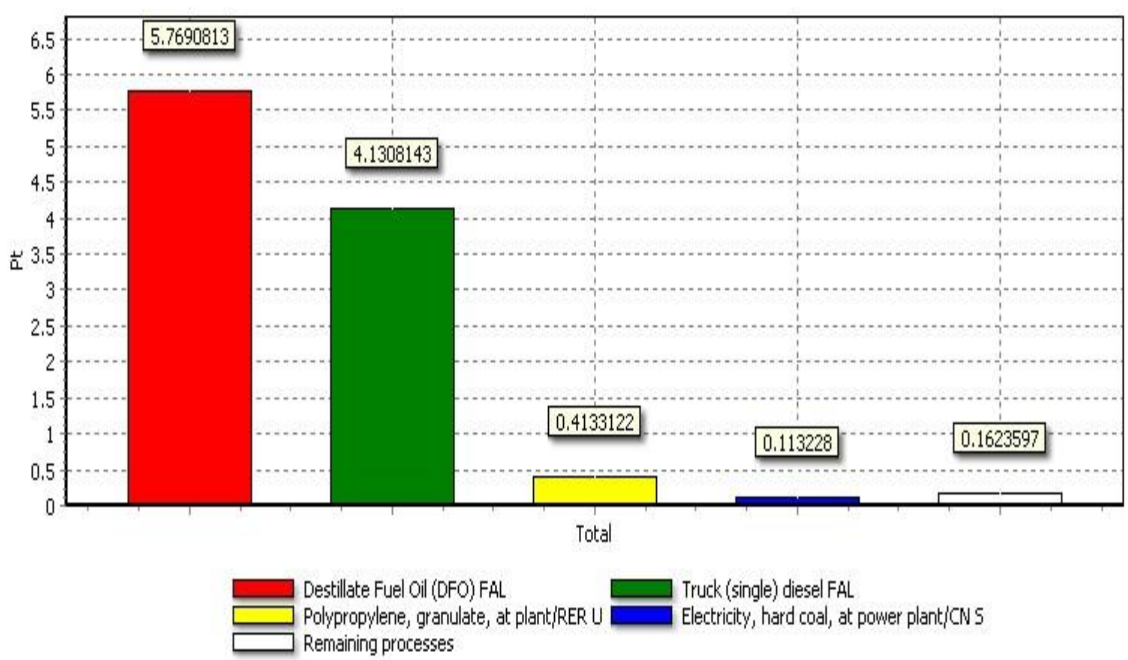


Figure 5-10 Hot-spots in the manufacturing process of Product B (Eco-indicator'99 method) (Cut-off value: 1%)

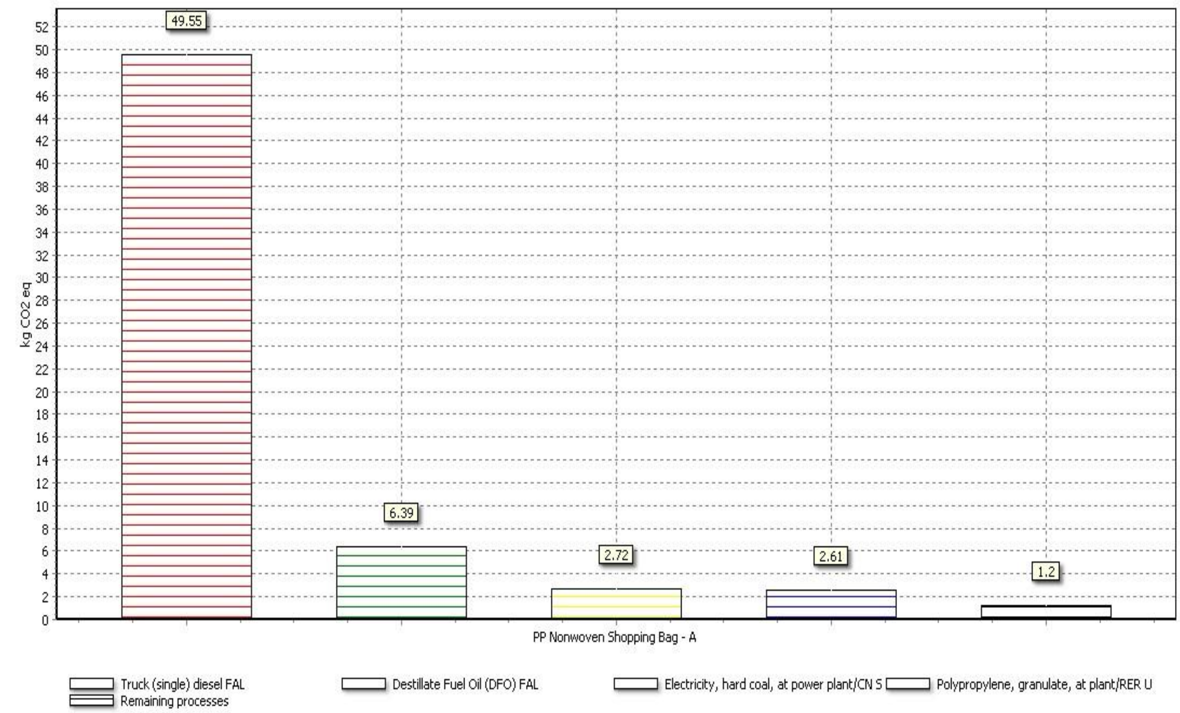


Figure 5-11 Hot-spots in the manufacturing process of Product A (Carbon footprint-GWP values of 20 Years)

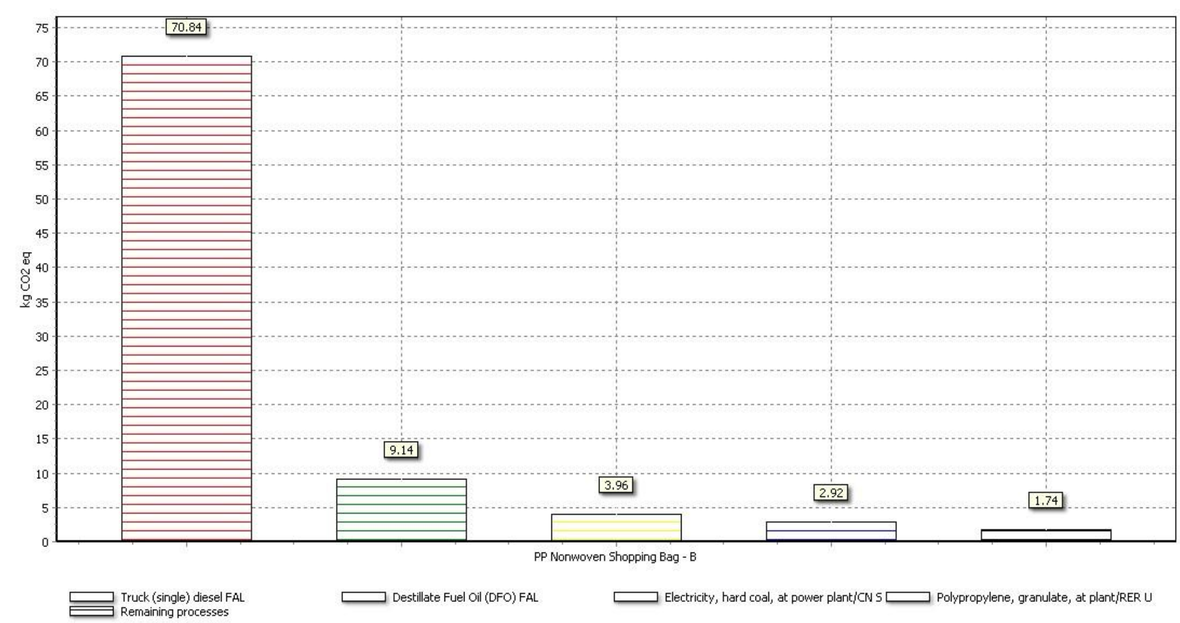


Figure 5-12 Hot-spots in the manufacturing process of Product B (Carbon footprint-GWP values of 20 Years)

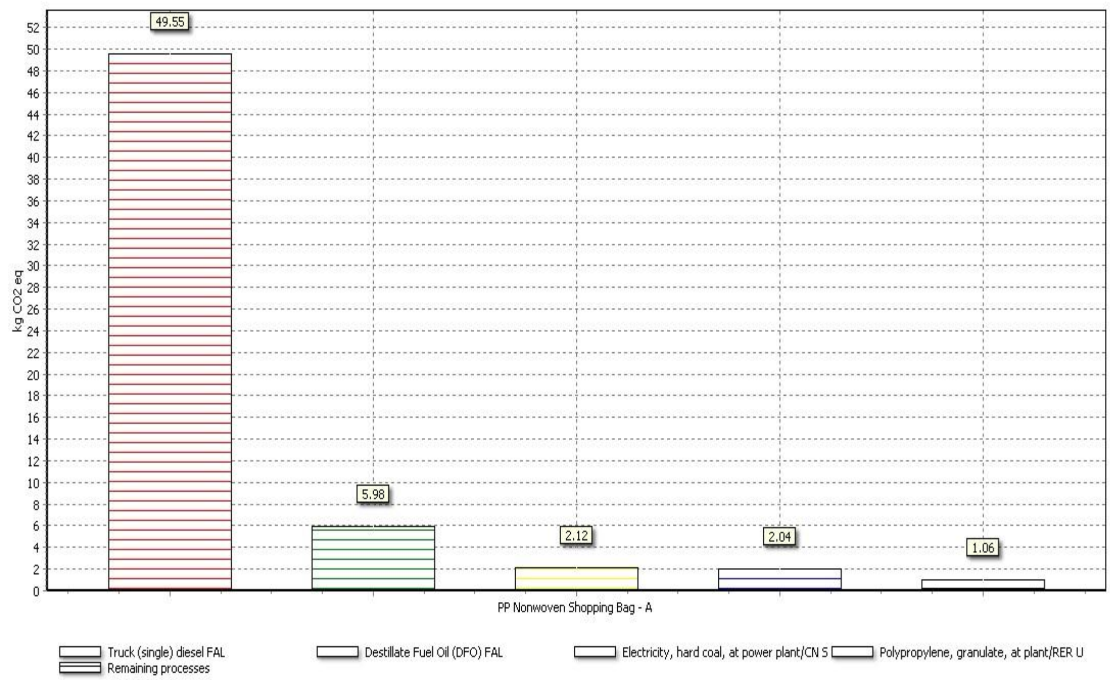


Figure 5-13 Hot-spots in the manufacturing process of Product A (Carbon footprint-GWP values of 100 Years)

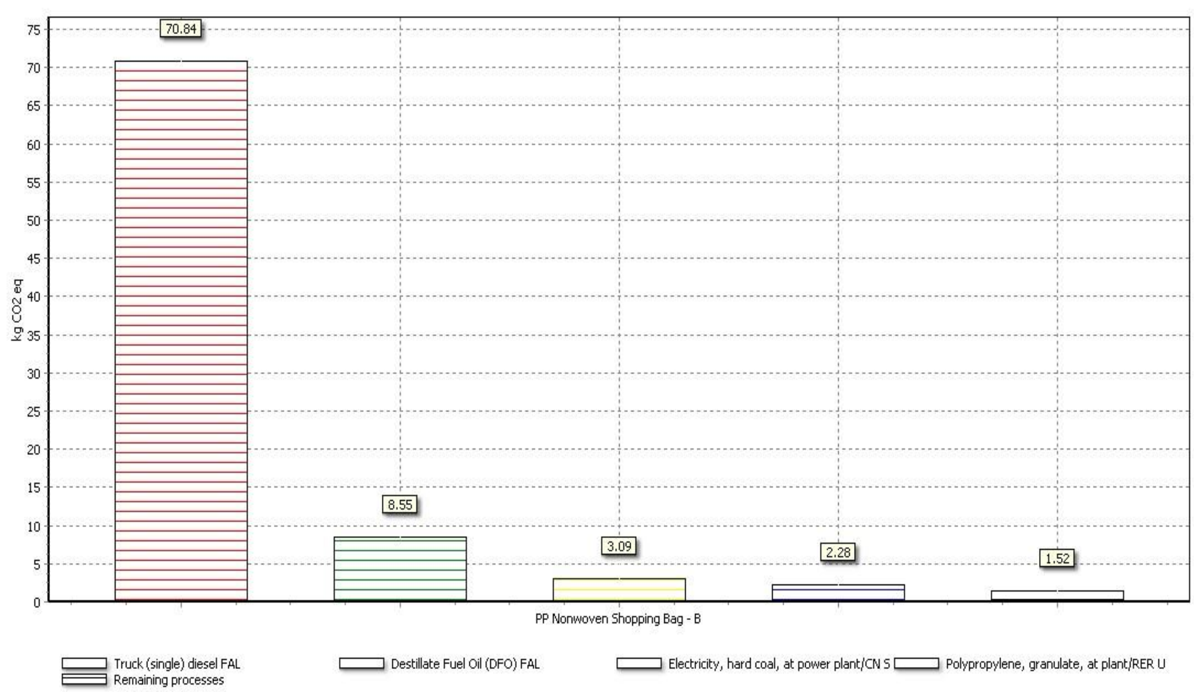


Figure 5-14 Hot-spots in the manufacturing process of Product B (Carbon footprint-GWP values of 100 Years)

5.4.4. Life Cycle Interpretation- Eco-damage assessment

Characterisation

In all the categories, product B is shown to be less environmentally friendly, since it causes major damage in all categories. From the normalization graph (Fig.5-6), it can be seen that products A and B created significant damage in two categories: respiratory inorganics and fossil fuels. Separate graphs are presented here to explain the impact of each product in terms of respiratory inorganics and fossil fuels.

Respiratory inorganics

Generally, the particulates, nitrogen dioxide and sulfur dioxide are the main threats to human respiratory health. Figs. 5-15 - 5-16 describe the major contributors for respiratory organics in the manufacturing sequences of A and B. Local transportation by means of diesel truck is the major threat here for both products. The secondary factor for inorganics for the products is the electricity consumed in the process of manufacturing and which obtained from burning coal.

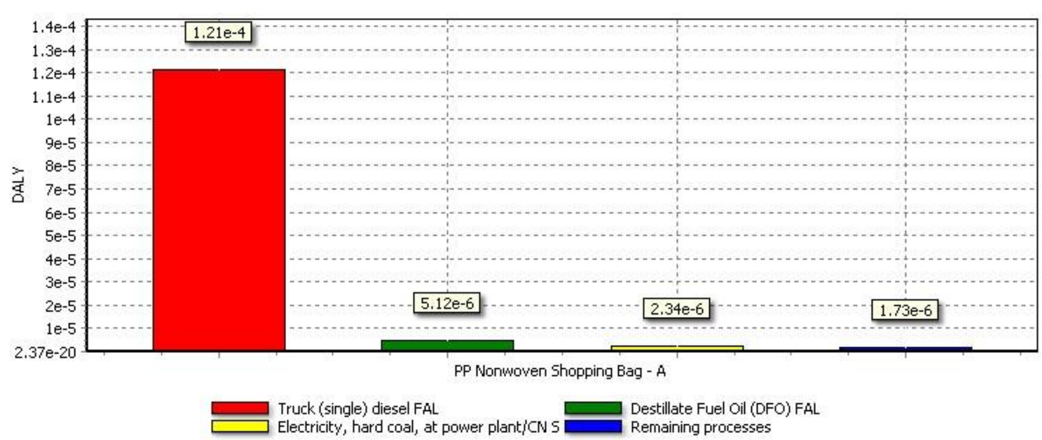


Figure 5-15 Contributing factors for respiratory inorganics of Product A

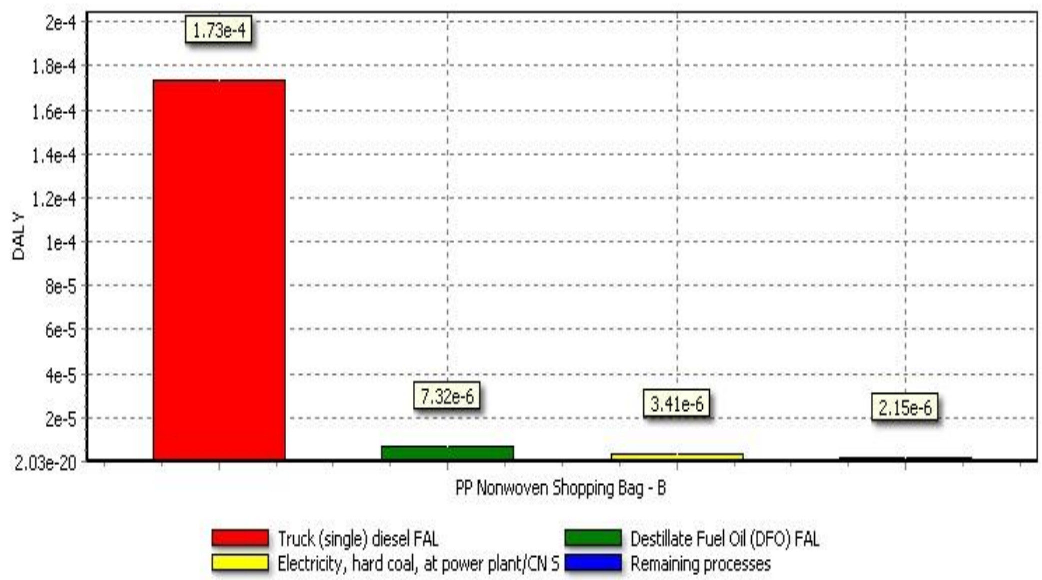


Figure 5-16 Contributing factors for respiratory inorganics of Product B

Fossil fuels

Fossil fuels such as coal, oil, and gas, are mainly used to generate electricity. The production of shopping bags, e.g. spun bonding in A and thermal attachment in B are energy consuming. Transportation is also a major consumer of energy. Figs. 5-17- 5-18 show the contributing factors to the impact of fossil fuel usage in A and B.

The use of diesel fuel for local transportation causes the major effect for both Products A and B. The next level of impact for both of the products in terms of fossil fuel consumption mainly comes from the PP chips manufacturing process. All the remaining processes involved combine to pose the third level of threat.

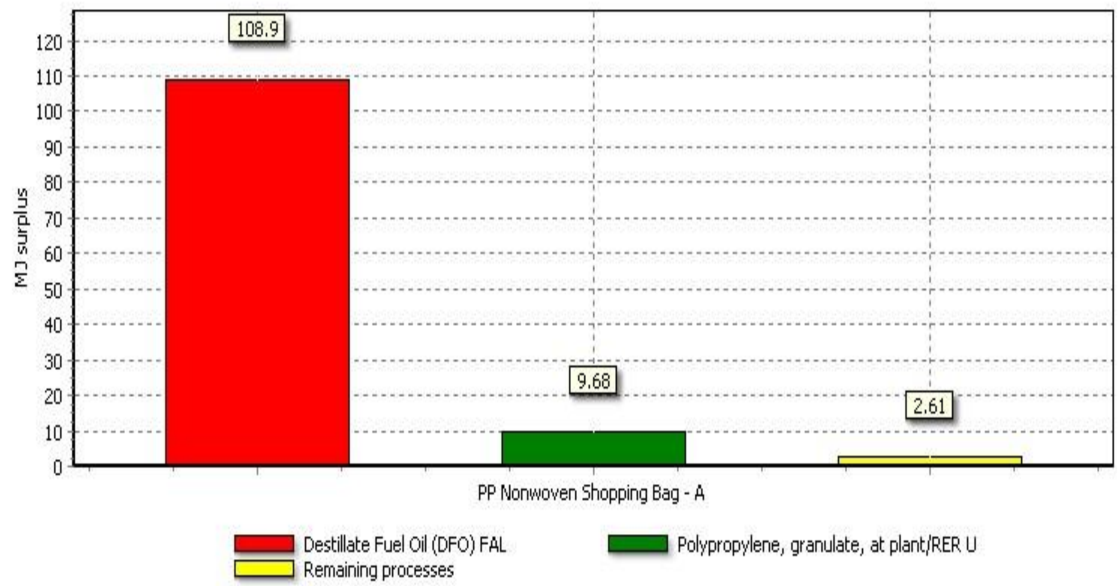


Figure 5-17 Contributing factors for fossil fuels of Product A

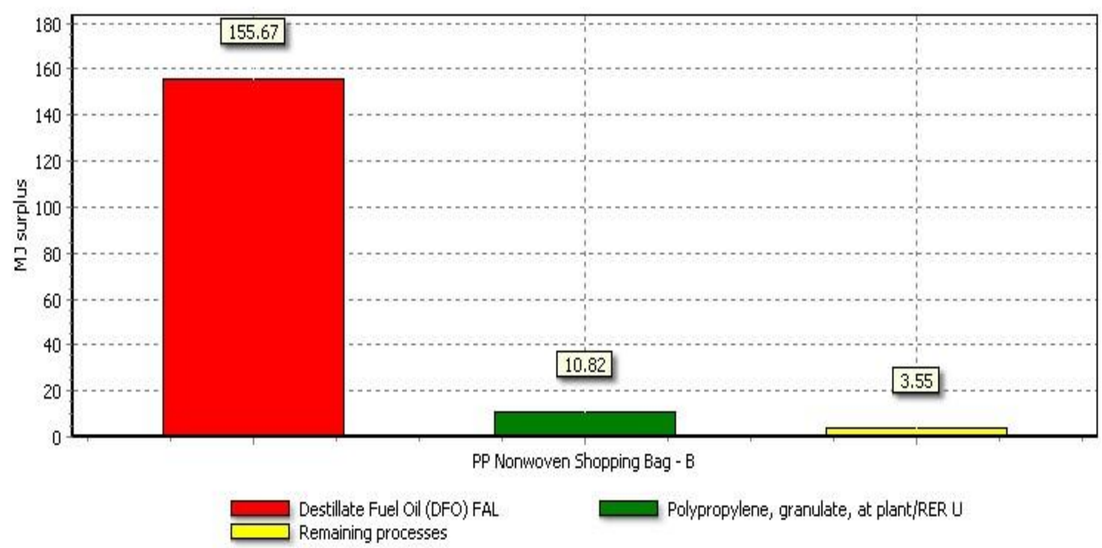


Figure 5-18 Contributing factors for fossil fuels of Product B

Normalization

This method helps to analyse and compare results in all the impact categories by reducing them to a common unit called the reference (or normal) value. In SIMAPRO, this step is made by multiplying the category impact by the reference, which in this case is the average yearly environmental load in a country or continent, divided by the number of inhabitants. The lowest score category is assigned the minimal value and the others respectively higher ones. In the analysis, the Eco-indicator 99 (H) v2.3 method, utilizing the normalization set of Europe EI 99 H/H has been implemented. The damage categories are normalized on a European level (damage caused by 1 European per year), based mostly on 1993 as the base year, with some updates for the most important emissions (Goedkoop et al., 2000 & 2001). Fig.5-6 shows that the major categories impacting the environment are: respiratory inorganics and fossil fuels. Respiratory inorganics such as nitrogen and sulfur oxides and others make the greatest impact on the environment. They are emitted mostly during the fuel burning process. The next greatest environmental impact is made by fossil fuels. This is caused mainly by the use of electricity during the whole process, which is produced from coal primarily but also from oil and gas. Concern about usage of fossil fuels is very particular to the usage of diesel during the transportation process and production process of PP, dyes used for screen printing for the manufacturing of shopping bags.

Single score results

Single score is the measure used to deduce the final result after comparing different products in the study. Though it cannot be used as a measure to market/display the environmental characteristics of comparable products, it certainly can provide an indication of different products' environmental scores.

Comparing products A and B, the former seems to be better in terms of environmental impact because of the low level of energy consumed during the manufacturing phase and the low level of waste fabric produced during manufacture. Product A surpasses B in terms of various inputs for its comparative unit weight. This can be very easily understood from the Life Cycle Inventory details and also from the process contribution graphs. It is evident from the results that sewing technology seems to be more efficient and less energy intensive compared to thermal technology.

5.4.5. Life cycle interpretation - Carbon footprint assessment

Tables 5.5 and 5.6 list the kgCO_2 equivalents (Global Warming Potentials-GWP) of both products A and B for 100 and 20 years respectively. Results show that product A is found to be better than product B in terms of carbon footprint assessment results (GWP values). The primary and other reasons for each product in contributing to GWP can be seen from Figs. 5-11 – 5-14 for 20 and 100 years. For both products, transportation by diesel trucks and the consumption of electricity for the production process of shopping bags as well as the energy intensive PP chips manufacturing process are found to be the major threats to global warming. Product A produced by conventional sewing technology, recorded a significantly lower carbon footprint results than product B.

From this detailed LCI analysis and carbon footprint assessment, Product A outscored Product B in terms of GWP, due to lower energy consumption, specifically during the sewing process compared to B made by thermal technology. The other major difference which attributes to the better position of Product A in terms of carbon footprint results can be clearly understood from the life cycle inventory details given in Table 5-4.

5.4.6. Conclusions and recommendations from LCA study

In this study, a comparative life cycle inventory (cradle to gate) was presented for two polypropylene nonwoven bags manufactured by two different technologies – conventional sewing technology and thermal attachment. The hot-spots in the manufacturing processes of the two products in question and also a comparative life cycle impact assessment study were performed. Environmental impacts were assessed from the cradle to gate stage of polypropylene nonwoven bags and within certain boundaries indicated earlier.

Of the two major technologies involved in manufacturing nonwoven shopping bags in the attachment phase compared in this study, it is clear that sewing technology is better in terms of environmental damage and carbon footprint than thermal technology. Product A, though it assumes more inputs in the spun-bonding process due to its higher unit weight, outscores B due to its lower energy requirements, low level of waste creation and other related factors in terms of comparative unit weight.

Concerning major hot-spots, transportation by diesel truck, manufacturing process impacts of polypropylene and the consumption of electricity are the major elements that impact the environment. Regarding polypropylene and the printing colour/dye used, nothing much can be done here, except advising the supplier from whom these are procured to take care of the environmental issues pertaining to the manufacturing impacts of the respective products. Also it is advised to procure from the closest manufacturers, though transportation impact is not included in this study.

Local transportation is found to be one of the major causes of environmental impacts and this is a two-fold issue. One is transporting the spun bonded fabrics to the cutting factory and the other one is procuring chemicals and other essential items for production. Though it is obligatory to transport spun bonded fabrics from one station to the other, it is strongly recommended to look for alternative renewable energy measures to curtail the negative impacts on the environment. It is also advised to look for a nearest dealer to reduce the transportation impact as far as procurement of chemicals and other items are concerned. In general, it is worthwhile implementing better alternatives/technologies to reduce power consumption to reduce the power impacts.

Though the majority of fabric waste is recycled, this study does not include the usage of recycled PP in its manufacturing phase, since it is difficult to account for calculations. If this were included, the impact assessment results may well be different and the impacts will certainly be reduced.

Certain hot-spots areas may not be controlled directly, such as the PP production process, electricity consumed for PP and dyes manufacturing processes and so on. But some processes such as local transportation of fabrics from one station to other and transportation involved in procurement of inventories for the manufacturing processes are under direct control. As discussed earlier, local transportation is one of the major threats here and it is better to look for the closest dealer to reduce the transportation impact. Though it is essential to transport the spunbond fabrics to the cutting factory, any alternative ways to transport using renewable energy sources could be of great help to curb carbon emissions. Alternatives/technologies to reduce power consumption need to be found to reduce the energy impacts and an energy audit may be recommended for this factory. In terms of product technology, it is advisable to select sewing technology, which was found to be better from this study in terms of carbon emissions. Customers can also be encouraged to opt for the products made by this technology.

5.5. Life cycle assessment of shopping bags – Manual calculation of LCA values for Chinese factors

In this study, quantification of environmental impacts is performed by well reputed commercial software called SIMAPRO from PRE Consultants of the Netherlands. Since the software originates from Europe, all the impact values are relevant to Europe and to people living there. Although SIMAPRO can quantify impact worldwide in addition to the specific impacts for Europe, there is no method to explicitly quantify the impacts of consumers in China. This is the case with most of the LCA packages, since many of them originated primarily from Europe. However, it is possible to select the inventory details pertaining to China from different datasets inbuilt with SIMAPRO. It is not possible, however, to quantify the characterization and normalization impact values for China alone.

Hence an attempt has been made in this study to perform the LCA calculations without the aid of LCA software. This attempt involved utilization of the well known equations used for the characterization step in LCA to calculate manually the impact values in this section. The characterisation and normalization values used in this section are solely applicable to China. Inventory details directly related to China are referred from the latest data source.

5.5.1. Life Cycle Inventory (LCI) details

For this study, five different types of shopping bags primarily used for grocery purposes are chosen to cover the major categories of plastic, paper, nonwoven and woven shopping bags. This study is confined to the cradle to gate stage of different shopping bags. LCI data for this study are obtained from the same sources discussed in section 5.3. Table 5-3 in section 5.3 lists the LCI data for the production of one unit of shopping bag. As seen from Table 5-3, major areas covered in LCI are the primary energy used to produce shopping bags and the GHG emitted during the production phase. These two factors are considered to quantify the environmental impacts pertaining to the impact values related to China.

The first one is the electricity input, for which the electricity inventory for China is referred to quantify the impacts corresponding to generation of energy. Data pertaining to electricity generation are taken from the latest possible source (Di et al., 2007). The electricity inventory, i.e. life cycle inventory for electricity generation in China to produce 1 kWh of energy is listed in Table 1 in Appendix 2. The emission inventory values were calculated from the electricity inventory from the values listed in Table 2 in Appendix 2 for different types of shopping bags in terms of the energy requirement values listed in Table 5-3. The second input in Table 5-3 is GHG emissions. GHG emissions of different shopping bags listed in Table 5-3 are directly considered and the results are separately listed in Table 5-7.

GHG Emissions in production process	Plastic bag (HDPE)	Paper bag (Kraft paper)	PP fibre nonwoven bag	Woven cotton bag	Boutique plastic (LDPE)
CO_2 eq.	11.6 grams	22.7 grams	472.0 grams	277.0 grams	45.8 grams

Table 5-7 Green house gas emission inventory per unit for shopping bags in production process (Nolan ITU et al., 2002; ExcelPlas Australia et al., 2004)

Combining the two inputs discussed above, Table 3 in Appendix 2 lists the quantified total inventory for the production processes of shopping bags. The results are expressed in kilograms per unit of bag.

5.5.2. Life cycle impact assessment

Characterisation

As a first step of characterisation, several impact categories are characterized in this research work. The first category is: environmental burden expressed in terms of environmental load units (ELU) and depletion of abiotic resources. ELU is expressed separately for natural resources, emissions to air, fresh water and sea water. The equation for the calculation of environmental burden is as follows (Guinee et al., 2002):

$$\text{Environmental Burden} = \sum_{i} \text{Factor}_i * m_i \quad [5.1]$$

The total environmental burden is expressed in Environmental Load Units. Factor $_i$ (ELU.kg^{-1}) is the valuation weighting factor for the EPS method for resource i, while m_i (kg) is the quantity of resource i used. The values for these impact categories are tabulated in Table 4 in Appendix 2. All the values listed in Table 4 in Appendix 2 are taken from the handbook of life cycle assessment (Guinee et al., 2002), except the value of gas for ELU- natural resources category, which is taken from another source of reference (Swerea, 2009). Table 5 in Appendix 2 lists the Chinese characterisation and normalization factors for ADP from the latest reference (Feng et al., 2009). The equation for the calculation of ADP is as follows (Guinee et al., 2002):

$$\text{Abiotic Depletion} = \sum_{i} ADPi * m_i \quad [5.2]$$

The indicator result is expressed in kg of the reference resource antimony. ADPi is the Abiotic Depletion Potential of resource i, while m_i (kg, except for natural gas and fossil energy) is the quantity of resource i used.

The values for carbon footprint (GWP_{100}), ozone depletion potential, human toxicity for air, fresh water, sea water, agricultural soil and industrial soil are listed in Table 6 in Appendix 2. Values for acidification, eutrophication, radiation and photo-oxidant chemical potential are listed in Table 7 in Appendix 2. The equations for the calculation of carbon footprint (GWP_{100}), ozone depletion potential, human toxicity for air, fresh water, sea water, agricultural soil and industrial soil are as follows (Guinee et al., 2002):

Carbon footprint:

$$\text{Climate Change} = \sum_{i} GWP_{a,i} * m_i \quad [5.3]$$

The indicator result is expressed in kg of the reference substance, CO_2. $GWP_{a,i}$ is the Global Warming Potential for substance i integrated over a specified number of years, while m_i (kg) is the quantity of substance i emitted.

Ozone depletion potential:

$$\text{Ozone Depletion} = \sum_{i} ODP_i * m_i \quad [5.4]$$

The indicator result is expressed in kg of the reference substance, CFC-11. ODP_i is the Ozone Depletion Potential for substance i, while m_i (kg) is the quantity of substance i emitted.

Human toxicity potential:

$$\text{Human toxicity} = = \sum_{i} \sum_{ecom} HTP_{ecom\,,\,i} * m_{ecom,\,i} \quad [5.5]$$

The indicator result is expressed in kg 1, 4-dichlorobenzene equivalent. $HTP_{ecom\,,\,i}$ is the Human Toxicity Potential (the characterisation factor) for substance i emitted to the emission compartment ecom (= air, fresh water, sea water, agricultural soil or industrial soil), while $m_{ecom,\,i}$ is the emission of substance i to medium ecom.

The equations for the calculation of Acidification, Eutrophication, Radiation & POCP are as follows (Guinee et al., 2002):

Acidification:

$$\text{Acidification} = \sum_{i} AP_{i} * m_{i} \quad [5.6]$$

The indicator result is expressed in kg SO_2 equivalents. AP_i is the Acidification Potential for substance i emitted to the air, while m_i is the emission of substance i to the air.

Eutrophication:

$$\text{Eutrophication} = \sum_{i} EP_{i} * m_{i} \quad [5.7]$$

The indicator result is expressed in kg PO_4^{3-} equivalent. EP_i is the Eutrophication Potential for substance i emitted to air, water or soil, while m_i is the emission of substance i to air, water or soil.

Photo-oxidant formation:

$$\text{Photo-oxidant formation} = \sum_{i} POCP_{i} * m_{i} \quad [5.8]$$

The indicator result is expressed in kg of the reference substance, ethylene. $POCP_i$ is the Photochemical Ozone Creation Potential for substance i, while m_i (kg) is the quantity of substance i emitted.

Ionising radiation:

$$\text{Radiation} = \sum_{ecomp} \sum_{i} \text{Damage Factor}_{ecomp,i} * a_{ecomp,i} \quad [5.9]$$

The indicator result is expressed in yr. Damage Factor $_{ecomp,i}$ ($yr.kBq^{-1}$)is the characterisation factor substance i emitted to ecomp based on DALYs, while a $_{ecomp,i}$ (kBq) is the activity of substance i emitted to compartment ecomp.

The characterisation results were calculated according to the values given in Tables 4-7 in Appendix 2 and according to the well known life cycle characterization equations. The characterization results for environmental load units for resources and emissions are listed in Tables 8 and 9 respectively in Appendix 2. Table 10 in Appendix 2 shows the depletion of abiotic resources as a reference to antimony and Table 11 in Appendix 2 explains the results of the depletion of abiotic resources with the Chinese characterization factors. Table 12 shows the results of carbon footprint result for 100 years and ozone depletion potential for various shopping bags. Tables 13-19 in Appendix 2 explain the results of human toxicity potential to different mediums and human toxicity in total. Table 20 in Appendix 2 lists the acidification, eutrophication, POCP and radiation results. Table 21 in Appendix 2 explains the results of other impacts specific to the emissions inventory pertaining to China.

Results of characterization:

Table 5-8 below shows the results of the characterization step.

Impact Category	Plastic bag (HDPE)	Paper bag (Kraft paper)	PP fibre nonwoven bag	Woven cotton bag	Boutique plastic (LDPE)
GWP 100 Years	1.19E-01	4.03E-01	3.50E+00	5.04E+00	4.46E-01

Ozone Depletion Potential	4.78E-06	1.69E-05	1.35E-04	2.12E-04	1.78E-05
Human Toxicity	6.86E-02	2.45E-01	1.96E+00	3.08E+00	2.59E-01
Acidification	1.28E-03	7.27E-03	3.63E-02	5.71E-02	4.80E-03
Eutrophication	7.49E-05	2.66E-04	2.11E-03	3.32E-03	2.79E-04
Photo-oxidant Chemical Formation	6.44E-05	2.28E-04	1.82E-03	2.86E-03	2.40E-04
Ionising Radiation	6.55E-11	2.32E-10	1.84E-09	2.90E-09	2.44E-10
Radioactive solid waste in m^3	2.95E-11	1.05E-10	8.31E-10	1.31E-09	1.10E-10
Coal fly ash	9.17E-03	3.25E-02	2.59E-01	4.07E-01	3.42E-02
Slag	2.06E-03	7.29E-03	5.80E-02	9.13E-02	7.67E-03
Emissions of waste water	1.44E-01	5.11E-01	4.06E+00	6.39E+00	5.37E-01
Depletion of Abiotic Resources	7.10E-04	2.52E-03	2.00E-02	3.15E-02	3.19E-03
Environmental Burden-ELU-Emissions	7.69E-03	2.61E-02	2.26E-01	3.26E-01	2.88E-02
Environmental Burden-ELU-Resources	4.71E-03	1.67E-02	1.33E-01	2.09E-01	4.98E-02
ADP-Chinese factors	1.17E-06	4.16E-06	3.24E-05	5.21E-05	4.40E-06

Table 5-8 Results of characterization by manual calculation of LCA

Normalization:

The next step in life cycle impact assessment is normalization. Unlike characterization, it is not a mandatory step, but it is important since it normalizes the characterized impact results to an average individual, making the impact assessment results more meaningful. Normalization is done by the following equation (Yang and Nielsen, 2001):

$$NP(j) = EP(j) / (T \times ER(j)) \quad [5.10]$$

where

EP(j) is the environmental impact potential for impact category j,

NP(j) is the normalised environmental impact potential for impact category j, T is the expected lifetime of the product in years,

ER(j) is the normalisation reference for impact category j.

Thus, as a result of the normalisation, all environmental impacts from the product are expressed as a fraction of an average person's yearly contribution to the impact, and the unit is milliperson equivalents, mPE.

So, $NP(j) = EP(j) / (1 \times ER(j)) = EP(j) / ER(j)$ [5.11]

Table 5-9 lists the values for normalization and weighting pertaining to China (Yang and Nielsen, 2001).

Impact category	Normalisation reference, ER90[3]				Normalisation reference unit	Weighting factor WFT2000[4]
	East	Central	West	China in total		
Global warming[1]	8,700				kg CO_2 eq/person/year	0.83
Ozone depletion[3]	0. 20[5]				kg CFC11 eq/person/year	2.7
Acidification[2]	35	33	41	36	kgSO_2-eq/person/year	0.73
Nutrient enrichment[2]	57	60	67	61	kgNO_3-eq/person/year	0.73
Photochemical ozone formation[2]	0.76	0.63	0.48	0.65	kgC_2H_4-eq/person/year	0.4
Bulk waste[2]	291	247	186	251	kg bulk waste/person /year	0.62
Hazardous waste[2]	22	17	15	18	kg hazard. waste/person/year	0.45
Slag and ashes[2]	18	21	16	18	kg slag and ashes/person/year	0.61

Table 5-9 Normalization & weighting values for China (Yang and Nielsen, 2001)

1) Reference region: World. 2) Reference region: East China, Central China, West China or China in total. 3) Reference year: 1990. 4) Target year: 2000

Chinese Factors for ADP are calculated by the following equation (Feng et al., 2009):

$$N = 1 / \sum_{2004} R_i * ADP_i \quad [5.12]$$

where N is normalization factor of abiotic resource depletion, Ri is reserves of the resource i (kg), $ADPi$ is characterization factors for the resource i (kg antimony eq. /kg), 2004 is the benchmark time the year of 2004.

On the basis of relative reserves of China's major resources, it can be calculated that the total resource reserves in 2004 are equal to 2.14×1010 kg antimony eq.and the normalization factor for resource depletion is therefore 4.67×10−11 (Feng et al., 2009).

Normalized results:

Table 5-10 below lists the normalized results for several impact categories from the values taken from Table 5-8. Table 5-11 shows the unnormalized results, for the impact categories where normalization values for China are not currently available.

Impact category	Plastic bag (HDPE)	Paper bag (Kraft paper)	PP fibre nonwoven bag	Woven cotton bag	Boutique plastic(LDPE)
GWP 100 Years- kg CO2 eq/person/year	1.37E-05	4.64E-05	4.02E-04	5.79E-04	5.13E-05
Ozone Depletion Potential- kg CFC11 eq/person/year	2.39E-05	8.47E-05	6.74E-04	1.06E-03	8.91E-05
Acidification- kgSO2- eq/person/year	3.56E-05	2.02E-04	1.01E-03	1.59E-03	1.33E-04
Photo-oxidant Chemical Formation- kgC2H4- eq/person/year	9.91E-05	3.51E-04	2.79E-03	4.40E-03	3.69E-04
Radioactive solid waste- kg hazard. waste/person/year	1.64E-12	5.83E-12	4.62E-11	7.28E-11	6.11E-12

Slag & ash- kg slag and ashes/person/year	5.19E-06	1.84E-05	1.46E-04	2.30E-04	1.93E-05
ADP Chinese Factors	4.89E-03	1.73E-02	1.38E-01	2.17E-01	1.82E-02
ADP-Chinese factors for norm-alisation figure of 4.67×10−11	2.51E+03	8.91E+03	6.94E+04	1.12E+05	9.42E+03

Table 5-10 Normalized results (milliperson equivalents)

Impact category	Plastic bag (HDPE)	Paper bag (Kraft paper)	PP fibre nonwoven bag	Woven cotton bag	Boutique plastic (LDPE)
Human Toxicity	6.86E-02	2.45E-01	1.96E+00	3.08E+00	2.59E-01
Eutrophication	7.49E-05	2.66E-04	2.11E-03	3.32E-03	2.79E-04
Ionising Radiation	6.55E-11	2.32E-10	1.84E-09	2.90E-09	2.44E-10
Depletion of Abiotic Resources	7.10E-04	2.52E-03	2.00E-02	3.15E-02	3.19E-03
Environmental Burden-ELU-Emissions	7.69E-03	2.61E-02	2.26E-01	3.26E-01	2.88E-02
Environmental Burden-ELU-Resources	2.33E-02	8.26E-02	6.57E-01	1.03E+00	8.69E-02
Emissions of waste water	1.44E-01	5.11E-01	4.06E+00	6.39E+00	5.37E-01

Table 5-11 Unnormalised results

Weighting:

The next step in impact assessment is weighting, which is done by the following equation (Yang and Nielsen, 2001):

$$WP\ (j) = WF\ (j) \times NP\ (j) \quad [5.13]$$

where

WP (j) is the weighted environmental impact potential for impact category j and

WF (j) is a weighting factor for environmental impact category j.

The results of weighting from the values taken from Table 5.7 are shown in Table 5-12.

Impact Category	Plastic bag (HDPE)	Paper bag (Kraft paper)	PP fibre nonwoven bag	Woven cotton bag	Boutique plastic (LDPE)
GWP 100 Years	1.14E-05	3.85E-05	3.34E-04	4.81E-04	4.26E-05
Ozone DepletionPotential	6.45E-05	2.29E-04	1.82E-03	2.86E-03	2.00E-04
Acidification	2.60E-05	1.47E-04	7.35E-04	1.16E-03	9.73E-05
Photo-oxidant ChemicalFormation	3.96E-05	1.41E-04	1.12E-03	1.76E-03	1.48E-04
Radioactive solid waste	7.38E-13	2.63E-12	2.08E-11	3.28E-11	2.75E-12
Slag & ash	1.27E-06	4.49E-06	3.57E-05	5.62E-05	4.72E-06

Table 5-12 Weighed results (milli person equivalents)

Verification of results with SIMAPRO 7.2

The results from the manual calculation were verified by the results of SIMAPRO 7.2. Results of characterization were compared, since the equation and the values for characterization are common. The results are shown in Tables 5-13- 5-19, which show the correlation of manually calculated and software generated results.

	Plastic bag (HDPE)	Paper bag (Kraft paper)	PP fibre nonwoven bag	Woven cotton bag	Boutique plastic(LDPE)
SIMAPRO	0.116	0.390	3.393	4.883	0.431
Manual	0.119	0.403	3.498	5.040	0.446

Table 5-13 Carbon footprint (results rounded-off)

	Plastic bag (HDPE)	Paper bag (Kraft paper)	PP fibre nonwoven bag	Woven cotton bag	Boutique plastic(LDPE)

SIMAPRO	0.001	0.005	0.038	0.060	0.005
Manual	0.001	0.007	0.036	0.057	0.005

Table 5-14 Acidification (results rounded-off)

	Plastic bag (HDPE)	Paper bag (Kraft paper)	PP fibre nonwoven bag	Woven cotton bag	Boutique plastic(LDPE)
SIMAPRO	7.57E-05	2.65E-04	2.11E-03	3.33E-03	2.78E-04
Manual	7.49E-05	2.66E-04	2.11E-03	3.32E-03	2.79E-04

Table 5-15 Eutrophication (results rounded-off)

	Plastic bag (HDPE)	Paper bag (Kraft paper)	PP fibre nonwoven bag	Woven cotton bag	Boutique plastic(LDPE)
SIMAPRO	6.56E-11	2.30E-10	1.83E-09	2.89E-09	2.41E-10
Manual	6.55E-11	2.32E-10	1.84E-09	2.90E-09	2.44E-10

Table 5-16 Radiation (results rounded-off)

	Plastic bag (HDPE)	Paper bag (Kraft paper)	PP fibre nonwoven bag	Woven cotton bag	Boutique plastic(LDPE)
SIMAPRO	4.84E-05	1.69E-04	1.35E-03	2.13E-03	1.78E-04
Manual	6.44E-05	2.30E-04	1.82E-03	2.86E-03	2.40E-04

Table 5-17 Photo-oxidant chemical formation (results rounded-off)

	Plastic bag (HDPE)	Paper bag (Kraft paper)	PP fibre Nonwoven bag	Woven cotton bag	Boutique plastic(LDPE)
SIMAPRO	6.45E-02	2.26E-01	1.80E+00	2.83E+00	2.37E-01
Manual	6.86E-02	2.45E-01	1.96E+00	3.08E+00	2.59E-01

Table 5-18 Human Toxicity (results rounded-off)

	Plastic bag	Paper bag (Kraft paper)	PP fibre nonwoven bag	Woven cotton bag	Boutique plastic(LDPE)

	(HDPE)				
SIMAPRO	6.97E-04	2.44E-03	1.94E-02	3.06E-02	2.56E-03
Manual	7.10E-04	2.52E-03	2.00E-02	3.15E-02	3.19E-03

Table 5-19 Abiotic Depletion (results rounded-off)

Comparative look between China and Europe

A manual life cycle impact calculation was performed and the results were presented in this chapter. Life cycle impact assessment was performed with the base of electricity and GHG emissions of manufacturing processes of various shopping bags. It is well known that the method of electricity generation (considering the same source) would be very different between China and Europe. The emission inventory values were calculated from the electricity inventory from the values listed in Table 2 in Appendix 2 for different types of shopping bags is very much specific to the electricity generation in China. Due to this, unique impact categories, such as depletion of abiotic resources in China, slag and ash, etc., pertaining to Chinese consumers were presented in this chapter in detail. Apart from this, the values for characterization, normalization and weighing for different parts of China for various impact categories were also presented in Table 5-9. Other results tabulated in Tables 5-13 - 5-19 presented the results of common impact categories characterized for Chinese values and the European values, taken from the database of SIMAPRO software.

5.6. Conclusions

In this chapter, life cycle inventory details of the production phase of shopping bags have been discussed from secondary data sources to test research question 2 given in Chapter 3. The details of a life cycle audit conducted to collect the primary data for

LCI are also dealt with and the eco-damage and carbon footprint assessment of nonwoven shopping bags are discussed from the primary data obtained from the in-depth field study. Manual life cycle assessment calculations pertaining to Chinese consumers are also discussed in this chapter.

Chapter 6 Consumer Behaviour and Assessment of Functional Properties of Shopping Bags

6.1. Introduction

Consumption behavior lies in the hands of consumers and is decided by the functionality of the product. This is also one of the important phases of life cycle of shopping bags, which is dealt within this chapter. As discussed in Chapter 2 and research question 3 listed in Chapter 3, there is a strong need to study the consumer behavior of shopping bags to gather data to build the end-of-life scenarios in LCA calculations, which has not been reported in the literature to date. Hence in this research work, an attempt has been made to study the consumer behavior in terms of shopping bag use in Mainland China, Hong Kong and India among different user groups to deduce the end-of-life scenario values, such as the percentage of recycle, reuse and disposal to landfill of various shopping bags. This issue addressed in detail in this chapter.

Various functional properties determine the functionality of shopping bag and ultimately its life time. Different test methods were used to test a range of functional properties of a variety of shopping bags. In this study, suitable test methods to test the functionality of various shopping bags were identified and tests were conducted. Also there is another property, which lies at the interface of functional and ecological properties, which I term here as, “Eco-functional” property, which is the reusability. Two other properties closely associated with this are impact strength and weight-holding capacity of shopping bags. So far there are no scientific instruments and methods to quantify these properties of shopping bags. This research developed an instrument to quantify the reusability, impact strength and weight-holding capacity of different shopping bags, which is discussed in this chapter.

Functional properties discussed above along with reusability influence consumer behavior in terms of deciding the useful life time of shopping bags. This study formulated research questions connecting these two and accordingly a life cycle inventory has been created for this phase of life cycle of shopping bags to be used to test research question 3 given in Chapter 3. The LCI is dealt within this chapter.

6.2. Eco-impact of shopping bags: consumer attitude and governmental policies

One of the major factors influencing the eco-impact of a product is its end-of-life scenario. The end-of-life phase is just as detrimental as the manufacturing phase for products like shopping bags which have limited life times. The disposal phase of any product attracts more importance in terms of its eco-impact compared to other phases in its entire life cycle. The same is also applicable to shopping bags. Human dimensions in consumer behaviour rule the decision of a product's disposal phase and consequently the eco-impact. Apart from human dimensions, governmental policies also assume significant importance in the environmental impact.

Consumer behaviour and governmental policies play an important role in the disposal stage of shopping bags. Usage and disposal stages may be categorized according to the following – reuse, recycle and disposal to the landfill. In spite of the fact that certain types of bags are designed to be recycled and reused, it is up to the customers to reuse a bag until it can be discarded or recycled, i.e., to reuse the shopping bags many times until they can be disposed of and to place them in recycling bins provided by the government, rather than dispose of them to landfill, which is detrimental to the environment and has a corresponding eco-impact. It is the responsibility of government to provide more recycling options and viable policies to facilitate recycling. Frequent promotion of recycling options by government and the modification of the behaviour of the consumer to ensure the reuse of the shopping bags until they are discarded is essential to reduce the eco-impact of these products.

The current trend of shopping bags preferred by consumers in the market can be categorized into 4 groups namely plastic, paper, woven and nonwoven bags according to the manufacturing technology and raw materials used. A plentiful array of raw materials, styles, designs are being employed to manufacture them which extends the sub types of shopping bags into an endless list. Ecological concerns are growing at high speed. People have started to look for eco-friendly/green products everywhere as a result of concern about the environment. Levies/stringent rules imposed by the government on non-eco friendly products show that ecological concerns are reaching a high level of prioritization.

There has been a dearth of research articles published on the subject of shopping bags as a whole. The only article published so far on consumer perception of shopping bags written on the basis of the attributes of shopping bags, is restricted to plastic and paper bags (Prendergast, et al., 2001). Previous studies dealing with LCA comparison of different shopping bags have yielded important findings (Ellis et al., 2005; Chaffee and Yaros, 2007; Carrefour, 2004; Ecobilan, 2008; FRIDGE; www.sustainability-ed.org;

Franklin Associates, 1990; GUA, 2005; Los Angeles County Department of Public Works, 2007; Nolan ITU et al., 2002; ExcelPlas Australia et al., 2004; James and Grant, 2005; The ULS Report, 2008; McGrath), but some studies included an end-of-life assumption to model the LCA of shopping bags which is very far from reality. The reality of the end-of-life scenario lies primarily in the hands of consumers. None of these studies reported the use of real data arising from recycling/reuse/landfill options of the consumers of shopping bags, which prompted the researcher's interest.

To fill these knowledge gaps, this research work focuses on the consumer's perception and behavior on the usage and disposal of various shopping bags (frequency of reuse, recycle of different shopping bags and also their propensity to dispose these to landfills) and also investigates the existing policy dimensions of government on recycling phase and other associated factors related to it. The discussion in this research work is also confined to different types of shopping bags, such as plastic, paper, nonwoven and woven bags.

Another important aim of this research work is to enable us to construct end-of-life scenarios in life cycle assessment by using real values from the actual users of shopping bags. The life cycle assessment of a product assumes greater significance in determining the eco-friendliness of the product. How a product is disposed of assumes equal significance to how a product is manufactured. Some of the previous studies conducted in this area to determine the life cycle of shopping bags (Ellis et al., 2005; Chaffee and Yaros, 2007; Carrefour, 2004; Ecobilan, 2008; FRIDGE; www.sustainability-ed.org; Franklin Associates, 1990; GUA, 2005; Los Angeles County Department of Public Works, 2007; Nolan ITU et al., 2002; ExcelPlas Australia et al., 2004; James and Grant, 2005; The ULS Report, 2008; McGrath)used an assumption which is very distant from reality. Hence to determine the attitude of users of shopping bags and to understand the disposal scenarios, a questionnaire survey was administered in Mainland China, Hong Kong and India among different user groups of shopping bags.

6.2.1. Design of the present research work

Fig.6-1 illustrates the whole structure of this research work (Muthu et al., 2010a). A huge amount of data is required in each phase of a product to perform Life Cycle Assessment. LCA covers different phases of a product life, from manufacturing to disposal. Data in terms of the quantity of raw materials required, energy needs, and amount of pollutants and wastes emitted, etc. are needed in each phase of a product to study the complete life cycle of a product. As depicted in Fig.6-1, the data related to manufacturing, transportation and distribution phases can be obtained from the group of manufacturers through direct observation of manufacturing process, data collection through surveys, interviewing the responsible staff or by secondary data from previous studies/ literature.

For the usage and disposal phases, however, the data should come from the actual users as human and policy dimensions play a crucial role here. Understanding of human and policy dimensions, which decide the use and end-of-life scenarios of different types of shopping bags, is essential to understand the eco-impact made by them. This study utilized the survey as a means to decipher human and policy dimensions.

6.2.2. Vision of the survey

As stated earlier, the aims of the survey lies in comprehending the usage and disposal behaviors of different types of shopping bags under discussion amongst different user groups. Usage and disposal behaviors are defined as how many times people reuse different shopping bags, what percentage of shopping bags can be recycled/ sent to landfill with the existing possibilities of recycling in their own country and what percentage of shopping bags people perceive can be reused/recycled/sent to landfill. Also this survey intends to comprehend the existing recycling options provided by the government and the willingness of people to support the government's policies further to improve the possibilities of recycling. This thesis reports the survey responses from different user groups of Mainland China, Hong Kong and India.

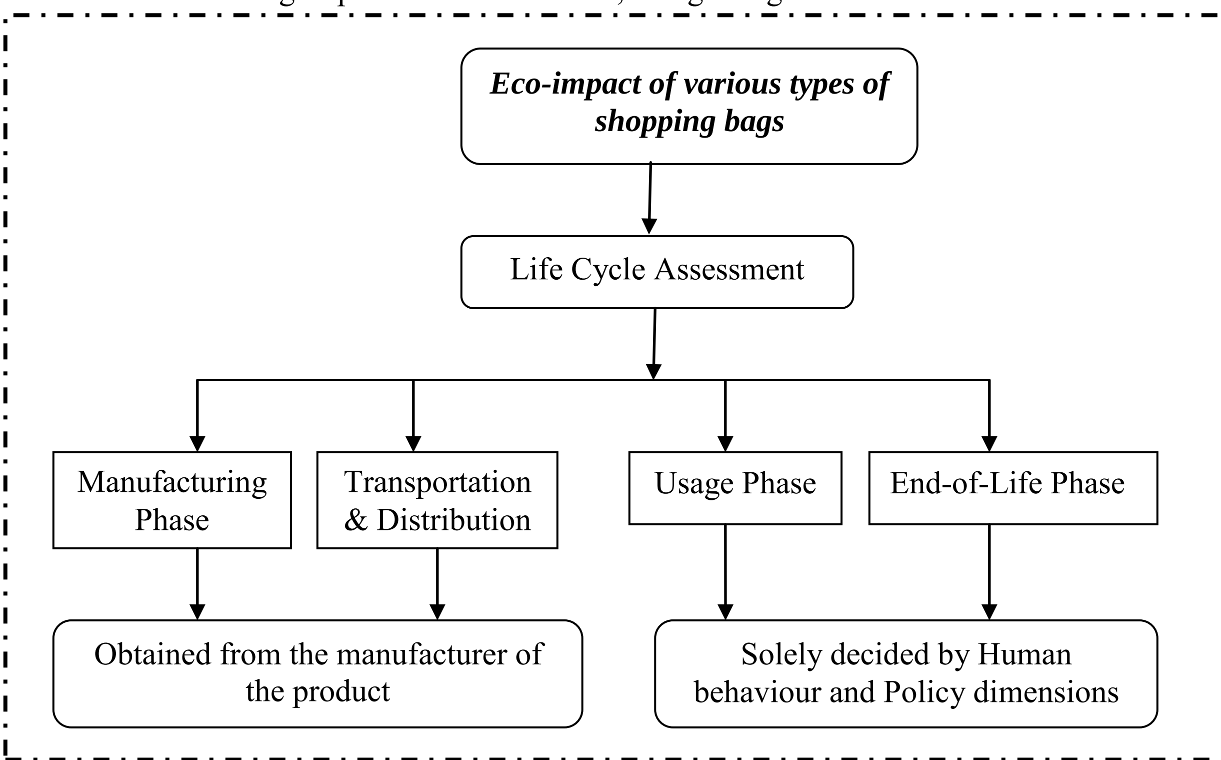


Figure 6-1 Design of the current study

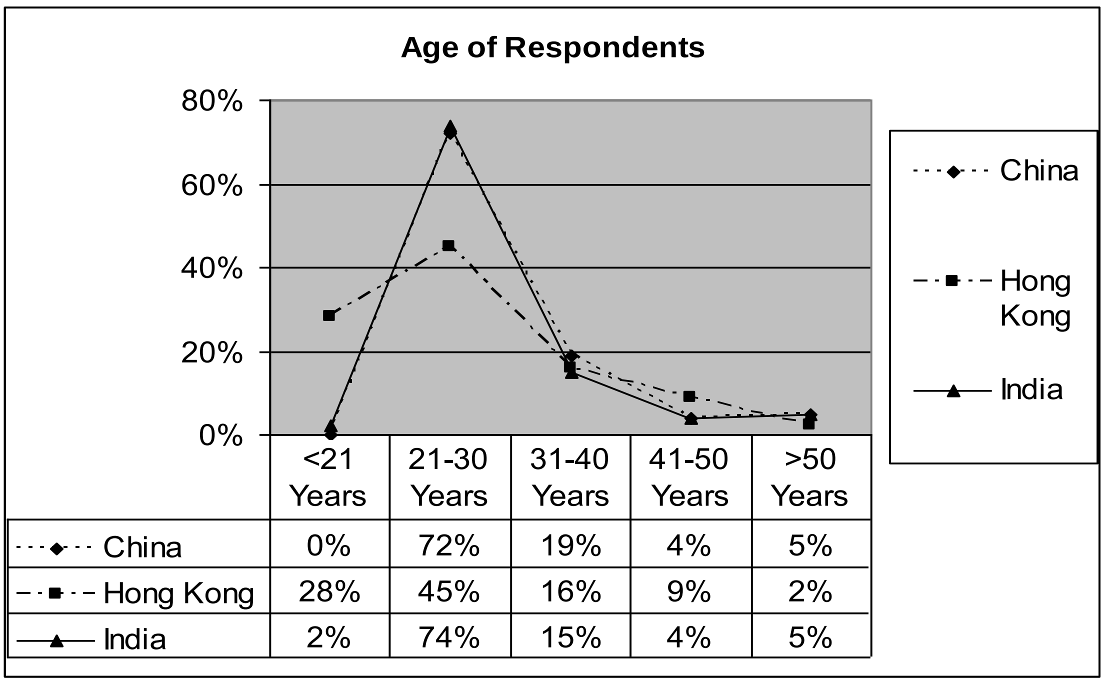
6.2.3. Respondents of research questionnaire survey

This survey was accomplished among students, homemakers and employed professionals in various fields of different age groups, who are users of shopping bags and also have knowledge about their usage and disposal behaviour in the countries under discussion. This survey was mainly aimed at understanding the consumer's perception of reuse, recycle and disposal to landfill, recycling possibilities with the existing government provisions/policies for recycling, willingness to support recycling systems/policies to reduce the percentage of disposal to landfill and so on. Convenience sampling method was chosen for this study and the survey was answered by 100 respondents from Mainland China and 125 respondents from India and Hong Kong. Respondents were contacted by electronic means and also in person. This survey had 9 questions pertaining to the usage and disposal of shopping bags and 4 questions pertaining to the personal particulars of respondents (refer Appendix 3).

Demographic profiles of respondents of survey

Personal particulars of the respondents from the three countries chosen for this study are shown in Figs.6-2 - 6-5 below. Fig.6-2 illustrates the age of respondents of survey, from which it can be understood that the majority of the respondents fall in the age group of 21-30 years in all the three countries under discussion. The gender of respondents can be found from Fig.6-3, where it can be seen that the majority of the respondents are females in Mainland China and Hong Kong while in India the majority of respondents are males. Fig.6-4 describes the profession of respondents. In Mainland China and India, the majority of the respondents are employed in various professions and in Hong Kong, the majority of the respondents are students. Fig.6-5 portrays the educational qualifications of respondents who answered the survey conducted for this study. In Mainland China and India, the majority of the respondents hold postgraduate degrees and in Hong Kong majority of the respondents holds undergraduate degrees. This shows the major limitation of this study: the demographic profile of the respondents is biased towards the young and educated population.

However, sampling the young and educated respondents could well indicate future trends in Asia. A large scale survey of the mass population in the selected countries for this study would reveal true overall behaviors.



	<21 Years	21-30 Years	31-40 Years	41-50 Years	>50 Years
China	0%	72%	19%	4%	5%
Hong Kong	28%	45%	16%	9%	2%
India	2%	74%	15%	4%	5%

Figure 6-2 Age of Respondents

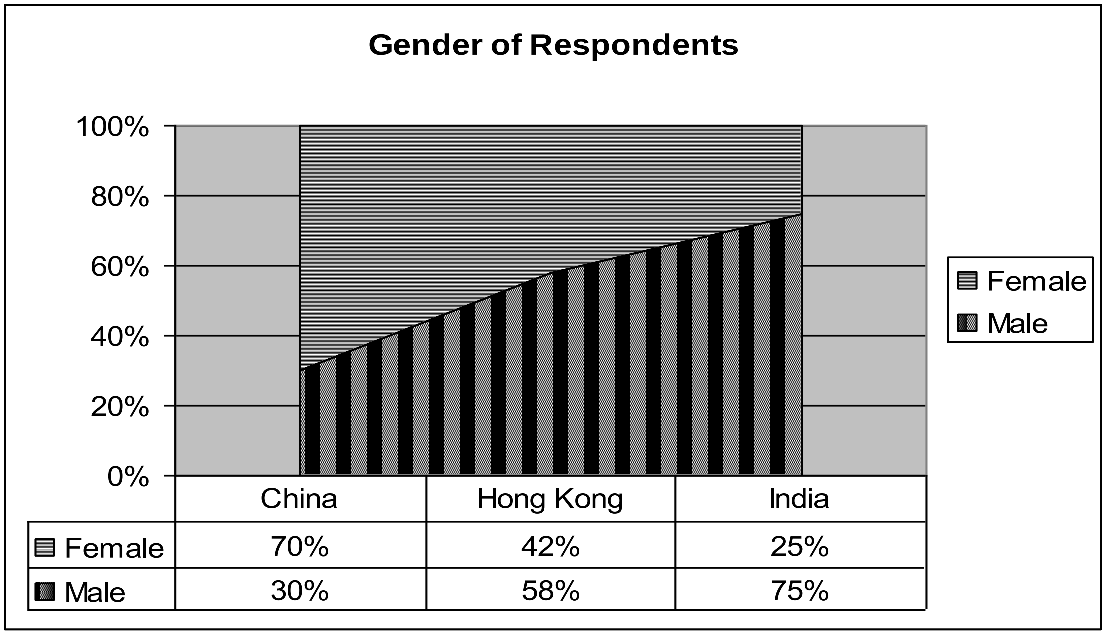


Figure 6-3 Gender of Respondents

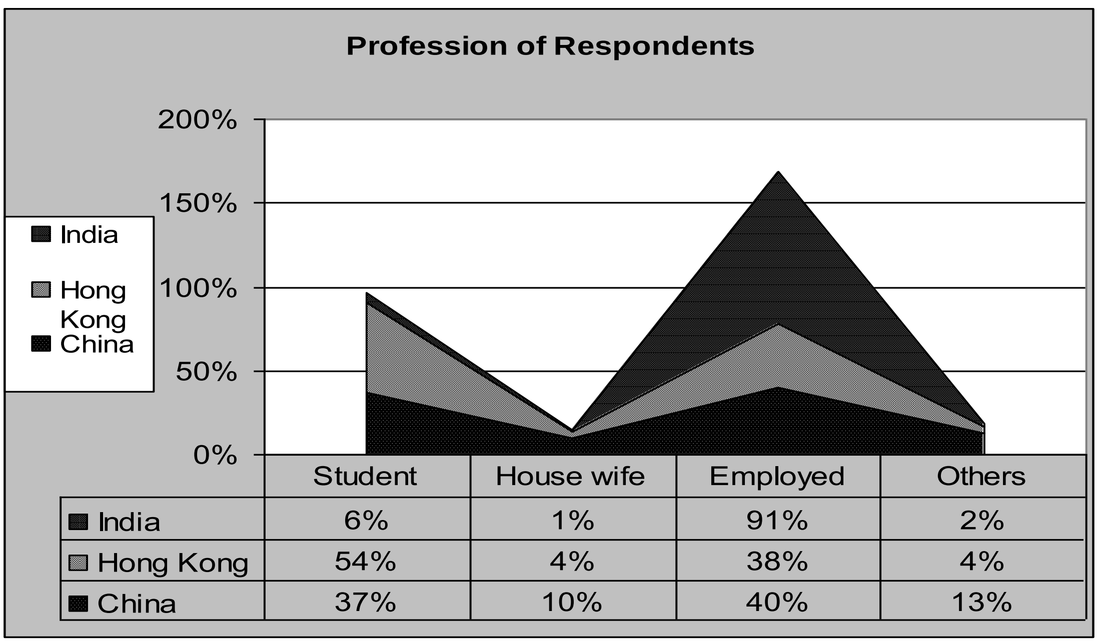


Figure 6-4 Profession of Respondents

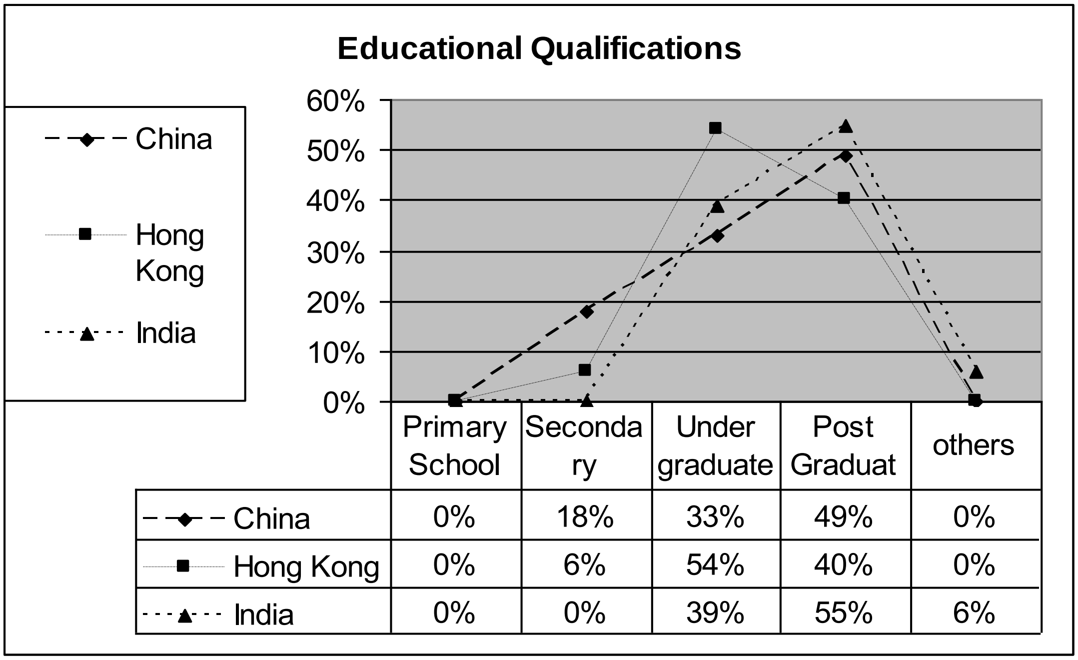


Figure 6-5 Educational Qualifications of Respondents

6.2.4. Usage and disposal behaviour of shopping bags

There are three major aspects in this investigation. They are:

Reusability

Recyclability

Disposal to Landfill

Reusability

The concept of reusability can be defined in two ways. One usual way is reuse of the product as a different one instead of discarding it to waste. For example, used nonwoven bags can be reused as liners/supportive covers in dust bins. The second way of defining reusability, which is usage of the particular product for the same purpose for which it is originally intended till it reaches its end of life or discarding stage, i.e. simply use the same product many times. This is imperative since it postpones the stage of discarding and delays the start of a new product while the first one is still being used.

The first one also holds good as far as dumping in landfill sites in the early stages is concerned. Even then, the second category deserves considerable appreciation since it is linked to the economy of an individual, along with the benefits already discussed. Therefore, it is the responsibility of manufacturers to employ suitable raw materials and manufacturing technology for a shopping bag to be reused many times, and it the responsibility of users to reuse the bag many times till it can be discarded.

Recyclability

This refers to the conversion of discarded bags after use into new products. This process involves breaking down the old items and producing the new products. This helps in the diminution of wastage of materials that have the potential to be used again and to trim the consumption of fresh raw materials. Other associated benefits are reduced cost, energy, pollution, etc. Here the government is accountable for providing policies/provisions which enable people to be motivated to opt for recycling of products rather than directly disposing them to landfill. However, in addition to governmental policies, public participation also matters greatly in augmenting the proportion of recycling.

Disposal to landfill

A landfill site is the final destination of all products once they can no longer be used. It is a place for the disposal of waste/garbage by interment. This is the origination of many problems pertaining to ecological problems like pollution of water and air, etc.

A major proportion of aspiration of eco-friendliness lies in the prevention of early entry of any product into landfill till it becomes completely useless.

6.2.5. Results and discussions

As discussed earlier, this survey was conducted among different user groups in Mainland China, Hong Kong and India. The results obtained are discussed below.

Perceived reusability of shopping bags

Figs. 6-6 - 6-7 exemplify the reusability of different types of shopping bags from the survey results. Fig.6-6 shows how many times respondents reuse plastic bags, from which it is clear that the respondents from Mainland China and Hong Kong prefer to use plastic bags twice and the Indians 3-5 times. Fig. 6-7 illustrates the reuse of paper bags, Chinese respondents desired to use paper bags 3-5 times and people from Hong Kong and India preferred twice and once respectively. Fig. 6-8 shows how many times respondents reuse nonwoven bags, from which it is clear that the respondents from Mainland China, Hong Kong and India prefer to use them 3-5 times. From Fig. 6-9, which illustrates the reuse of woven bags, respondents in Mainland China and India chose to use woven bags >5 times and respondents from Hong Kong 3-5 times. These results portray a mixed behaviour, which is not being appropriate to represent the actual reuse values of both bags. It is essential to calculate an effective percentage of reuse as a reflection of all values represented here.

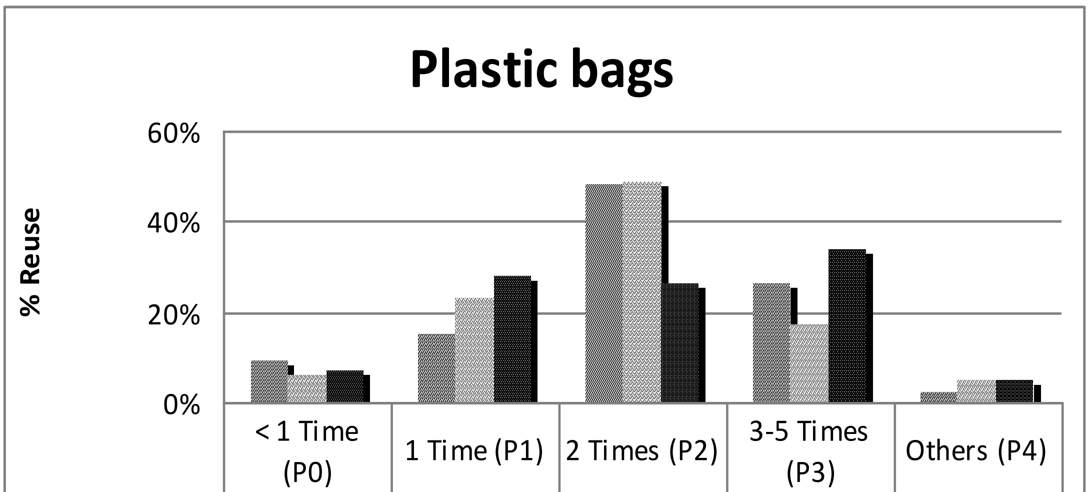
Hence two equations were framed to calculate the potential reuse of shopping bags. In equation 1, the corresponding percentage of <1 and 1 time usage is considered as 100%, 2 times as 50%, 3-5 times as 25% and others (> 5 times) is based on an average considered to be 10%:

ρ= Total Disposal % = P_0*100% + P_1*100% + P_2*50%+ P_3*25%+ P_4*10 %------ (1)

Reuse % = 100-ρ-- (2),

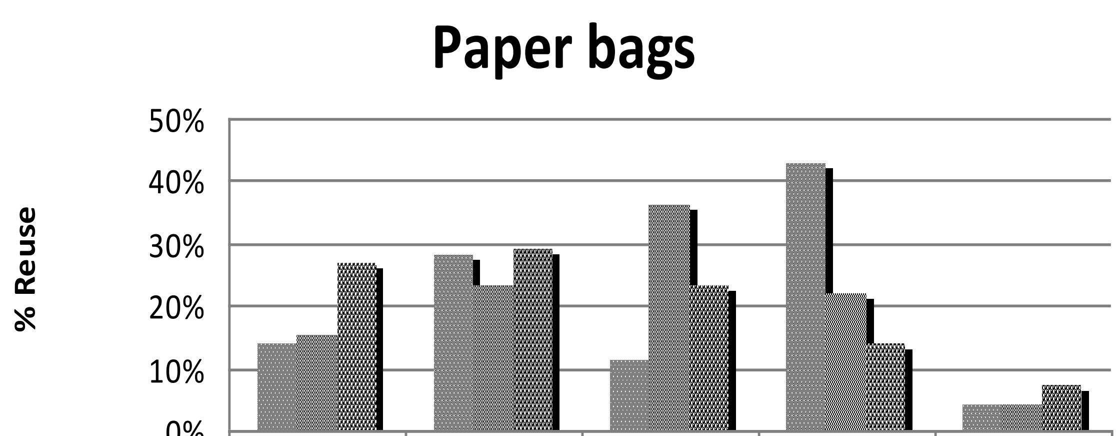
where P_0 is the percentage of reuse for < 1 time and so on. Please refer to Figs. 6-6 - 6-9 for the definitions of other indices.

Fig.6-10 illustrates the effective percentage of reuse values of different shopping bags of the three countries. From Fig.6-8, it is understood that on comparative grounds, woven bags are reused many more times than the other bags.



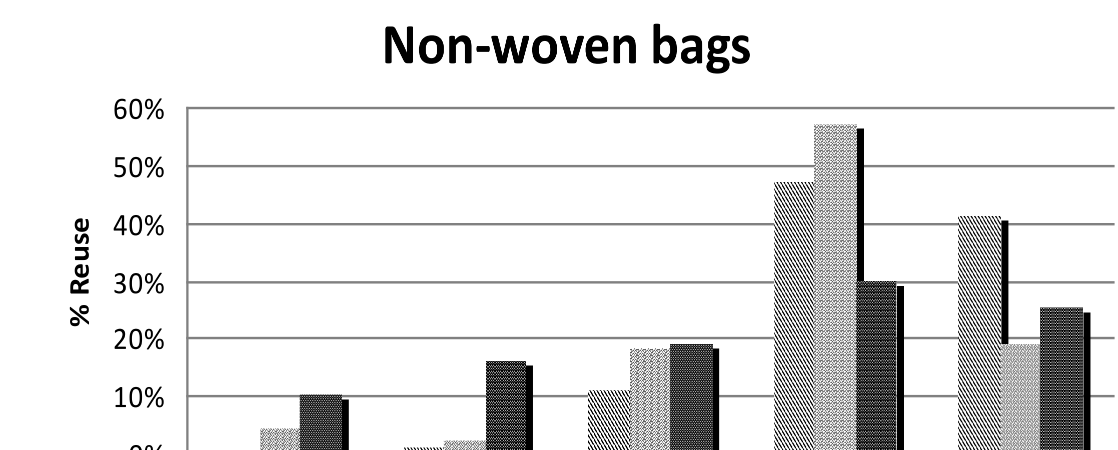
	< 1 Time (P0)	1 Time (P1)	2 Times (P2)	3-5 Times (P3)	Others (P4)
China	9%	15%	48%	26%	2%
Hong Kong	6%	23%	49%	17%	5%
India	7%	28%	26%	34%	5%

Figure 6-6 Perceived reusability of plastic bags



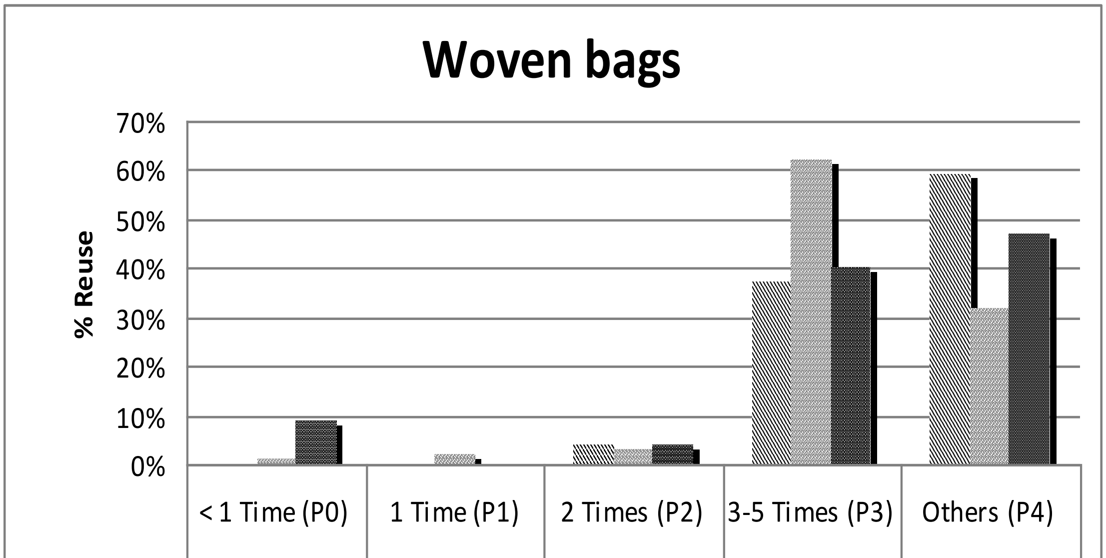
	< 1 Time (P0)	1 Time (P1)	2 Times (P2)	3-5 Times (P3)	Others (P4)
China	14%	28%	11%	43%	4%
Hong Kong	15%	23%	36%	22%	4%
India	27%	29%	23%	14%	7%

Figure 6-7 Perceived reusability of paper bags



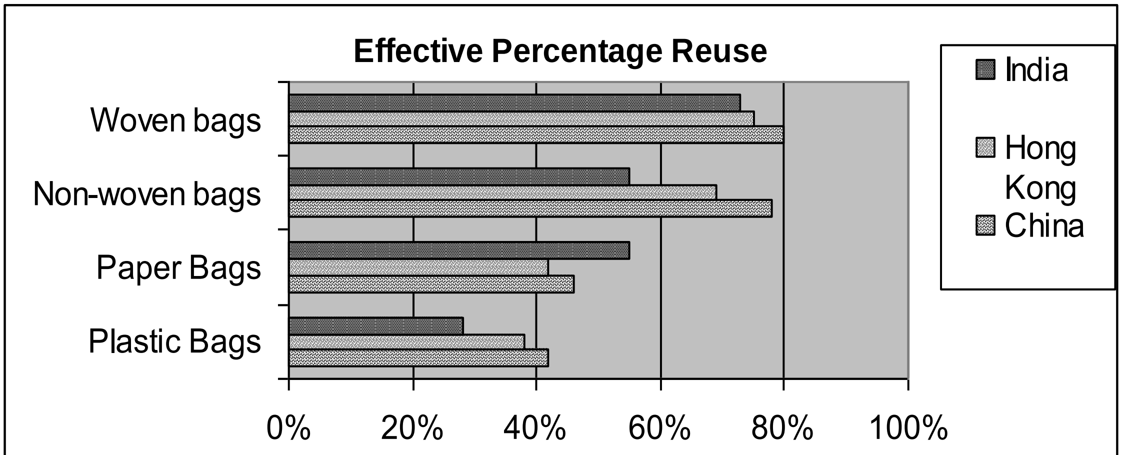
	< 1 Time (P0)	1 Time (P1)	2 Times (P2)	3-5 Times (P3)	Others (P4)
China	0%	1%	11%	47%	41%
Hong Kong	4%	2%	18%	57%	19%
India	10%	16%	19%	30%	25%

Figure 6-8 Perceived reusability of nonwoven bags



	< 1 Time (P0)	1 Time (P1)	2 Times (P2)	3-5 Times (P3)	Others (P4)
China	0%	0%	4%	37%	59%
Hong Kong	1%	2%	3%	62%	32%
India	9%	0%	4%	40%	47%

Figure 6-9 Perceived reusability of woven bags



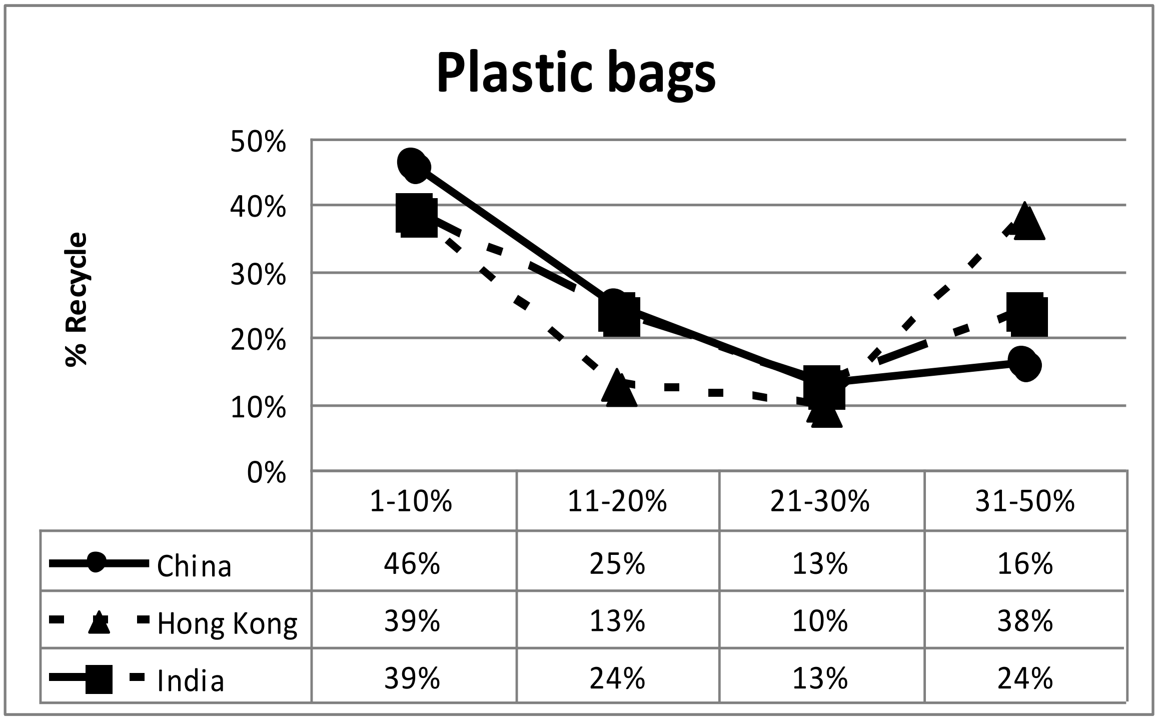
	Plastic Bags	Paper Bags	Non-woven	Woven bags
India	28%	55%	55%	73%
Hong Kong	38%	42%	69%	75%
China	42%	46%	78%	80%

Figure 6-10 Perceived effective percentage of reuse

Perceived percentage of shopping bags that can be recycled under the existing recycling possibilities provided by government

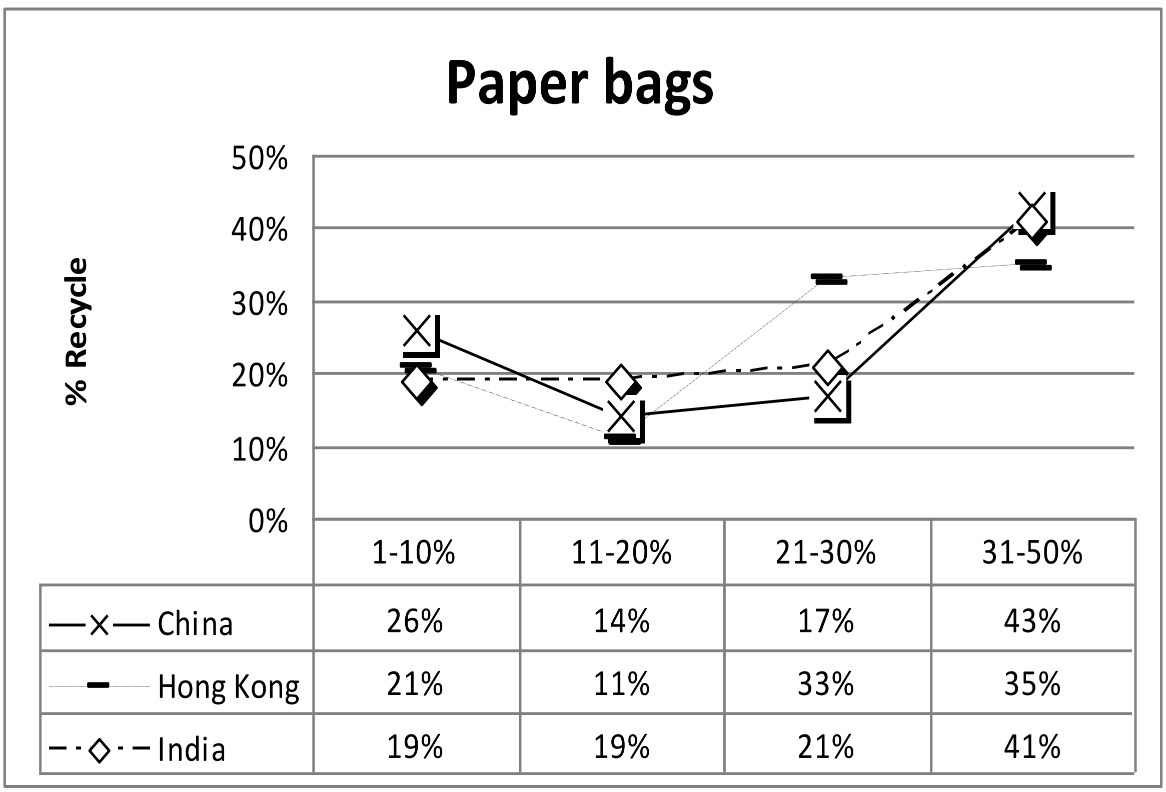
The second part of this survey attempts to determine the percentage of recycling of shopping bags possible with the existing recycling options available in Mainland China, Hong Kong and India. The survey results are presented in Figs.6-11 – 6-14. Fig.6-11 presents the recycling possibilities existing for plastic bags and Fig. 6-12 for paper bags. At the maximum 10% of plastic bags and 50% of paper bags can be recycled in all countries listed here. Fig. 6-13 shows the recycling possibilities existing for nonwoven bags and Fig.6-14 for woven bags. At the maximum, 21-30% of nonwoven bags can be recycled in Mainland China, 31-50% in Hong Kong and 21-30% in India. Similarly for woven bags, at the maximum, 31- 50% in Mainland China, Hong Kong and India can be recycled. Again, it is necessary to have an effective recycling percentage represented by the values in all categories, which was derived by weighted average method and presented in Fig. 6-15.

Fig. 6-15 shows that a maximum of 22% of plastic bags and 31% of paper bags can be recycled with the existing possibilities. The case is the reverse of reuse behaviour here. People prefer to recycle paper bags more than plastic bags. In fact, the potential recycling rate of plastic bags is less than paper bags and the reason for this to be investigated in detail. Also 22% of nonwoven bags in Mainland China, 25% in Hong Kong and 21% in India as well as 20% of woven bags in Mainland China, 23% in Hong Kong and 27% in India can be recycled under existing conditions.



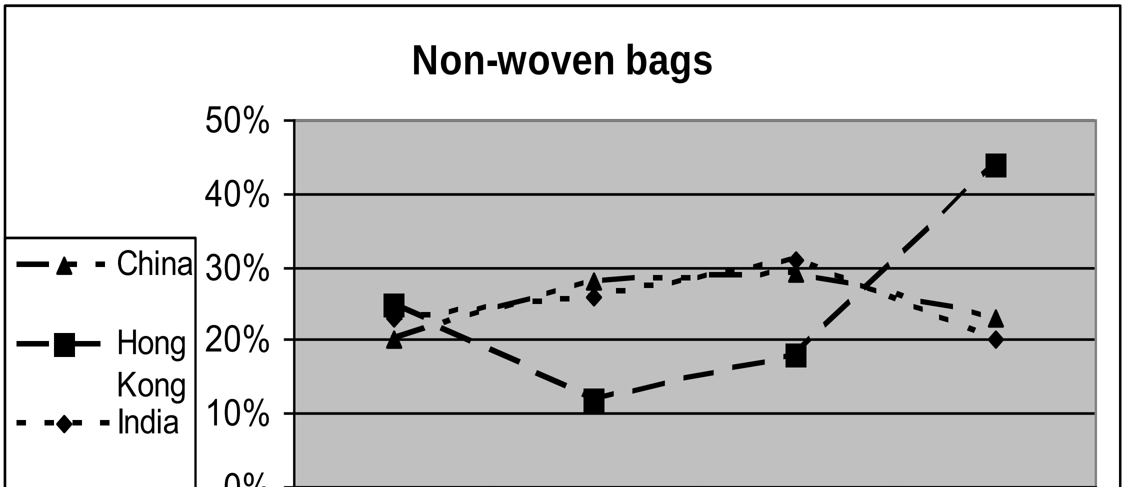
	1-10%	11-20%	21-30%	31-50%
China	46%	25%	13%	16%
Hong Kong	39%	13%	10%	38%
India	39%	24%	13%	24%

Figure 6-11 Perceived percentage of recycling of plastic bags



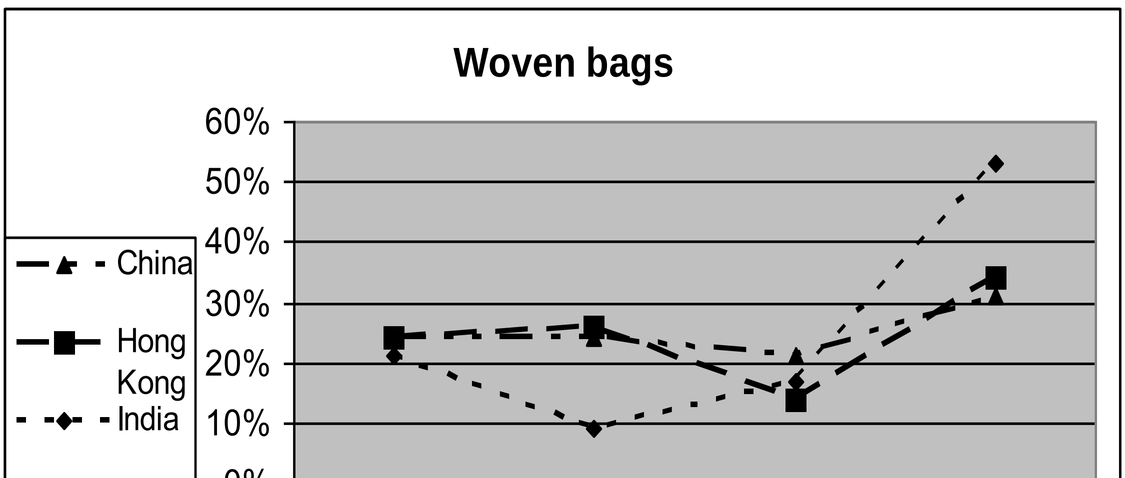
	1-10%	11-20%	21-30%	31-50%
China	26%	14%	17%	43%
Hong Kong	21%	11%	33%	35%
India	19%	19%	21%	41%

Figure 6-12 Perceived percentage of recycling of paper bags



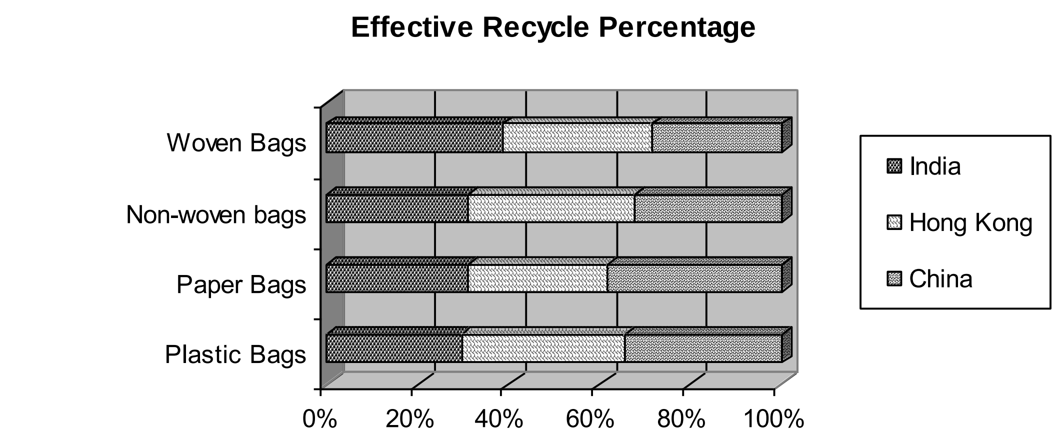
	1-10%	11-20%	21-30%	31-50%
China	20%	28%	29%	23%
Hong Kong	25%	12%	18%	44%
India	23%	26%	31%	20%

Figure 6-13 Perceived percentage of recycling of nonwoven bags



	1-10%	11-20%	21-30%	31-50%
China	24%	24%	21%	31%
Hong Kong	24%	26%	14%	34%
India	21%	9%	17%	53%

Figure 6-14 Perceived percentage of recycling of woven bags

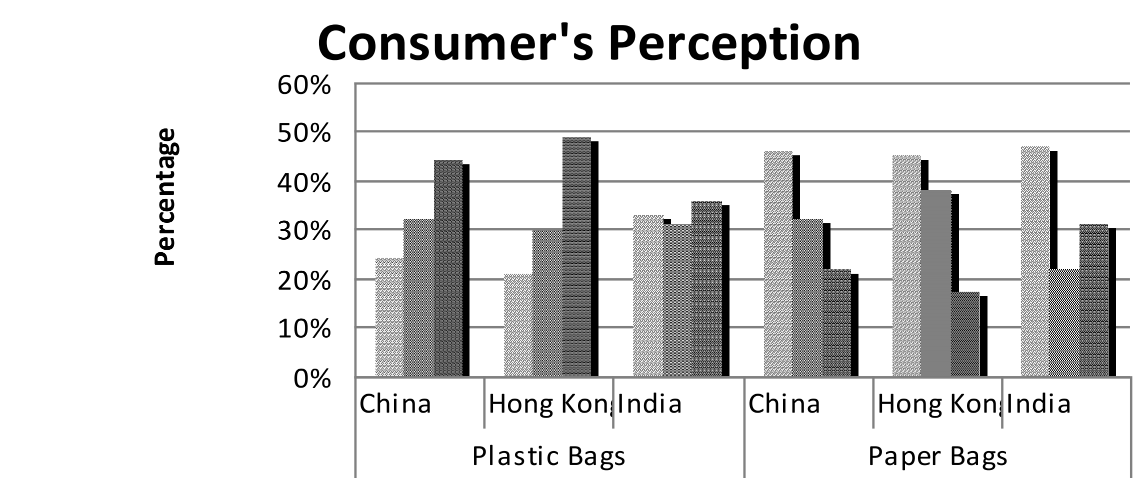


	Plastic Bags	Paper Bags	Non-woven bags	Woven Bags
China	21%	31%	22%	20%
Hong Kong	22%	25%	25%	23%
India	18%	25%	21%	27%

Figure 6-15 Perceived effective recycling percentages

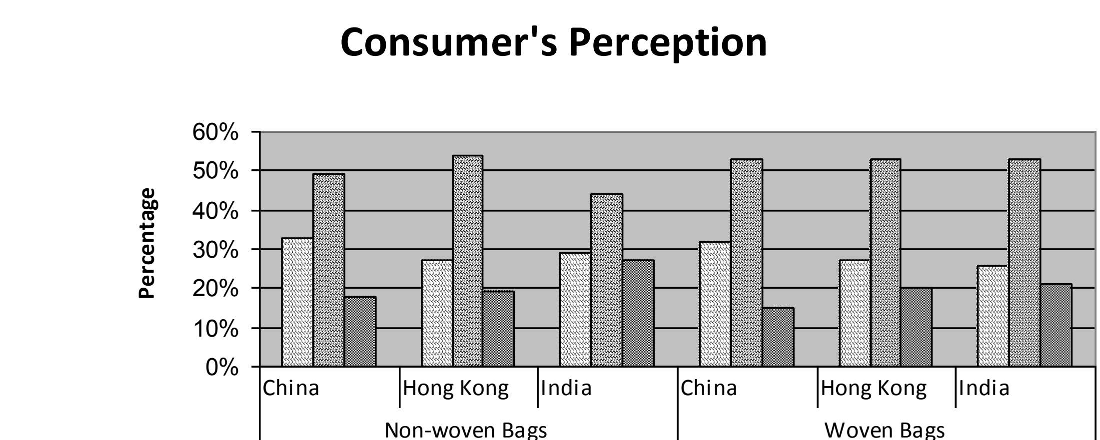
Perceived percentage of shopping bags can be recycled/ reused/sent to landfill

This part of the survey covers the response from the respondents to understand what percentage of shopping bags people perceive can be sent to recycle/reuse/sent to landfill. The results in this category for plastic and paper bags are described below in Fig. 6-16. Fig.6-17 shows the results for nonwoven and woven bags. These results can be directly employed for disposal scenarios while performing the life cycle analysis of different shopping bags, which is the main part of this survey.



	Plastic Bags China	Plastic Bags Hong Kong	Plastic Bags India	Paper Bags China	Paper Bags Hong Kong	Paper Bags India
Recycle%	24%	21%	33%	46%	45%	47%
Reuse%	32%	30%	31%	32%	38%	22%
Disposal for Landfill%	44%	49%	36%	22%	17%	31%

Figure 6-16 Perceived percentage of plastic and paper bags that can be recycled/ reused/sent to landfill



	Non-woven Bags China	Non-woven Bags Hong Kong	Non-woven Bags India	Woven Bags China	Woven Bags Hong Kong	Woven Bags India
Recycle%	33%	27%	29%	32%	27%	26%
Reuse%	49%	54%	44%	53%	53%	53%
Disposal for Landfill%	18%	19%	27%	15%	20%	21%

Figure 6-17 Perceived percentage of nonwoven and woven shopping bags that can be recycled/ reused/sent to landfill

Provision of recycling system/ policy by government

Fig. 6-18 reveals the provision of recycling systems in India, Hong Kong and Mainland China. In all these countries, most respondents voted for provision of recycling systems in their respective countries. Even though a majority of the respondents voted for provision of recycling systems, some reported that there is in fact no provision currently. This finding which may be due to the ignorance of the respondents or the existing systems may not fulfill their expectations. This needs to be further investigated.

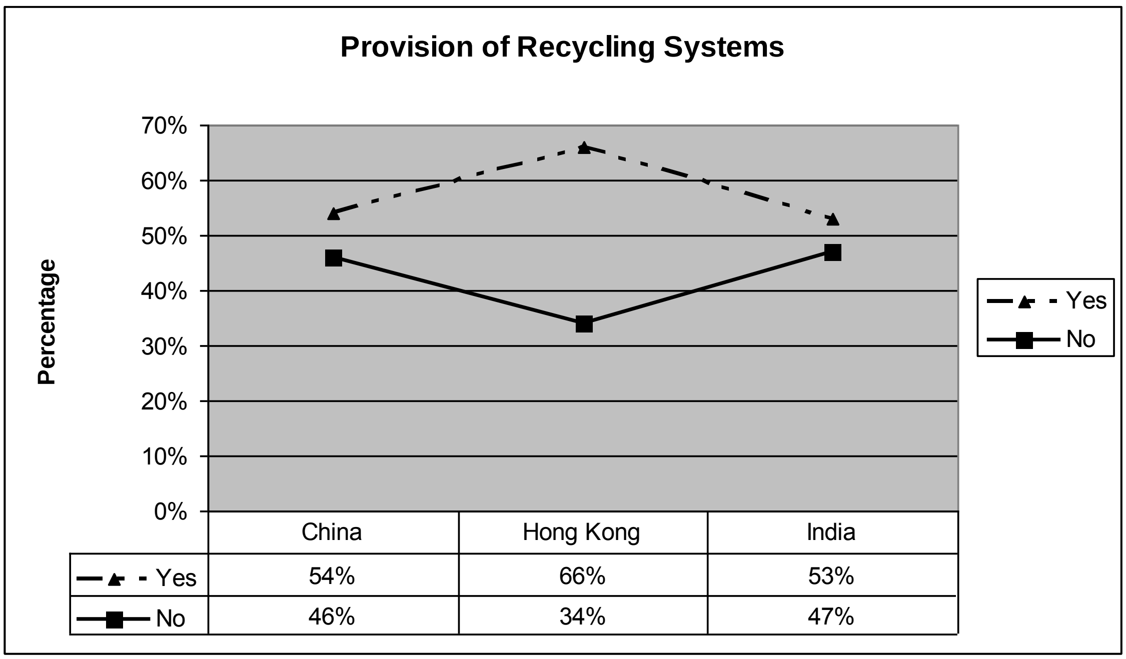


Figure 6-18 Provision of recycling systems

Willingness of people to support recycling policy / system to reduce the landfill percentage

In addition to government's efforts, the willingness of the people to support recycling system/policy matters a great deal to address environmental issues effectively. Fig. 6-19 describes the results derived in this category. Respondents from Mainland

China and Hong Kong are 100% willing to support recycling system/policy, but only 95% of Indians are willing to support the system. Though this is a negligible amount, taking into account the sample size, people in India need to be educated about eco-systems and impacts.

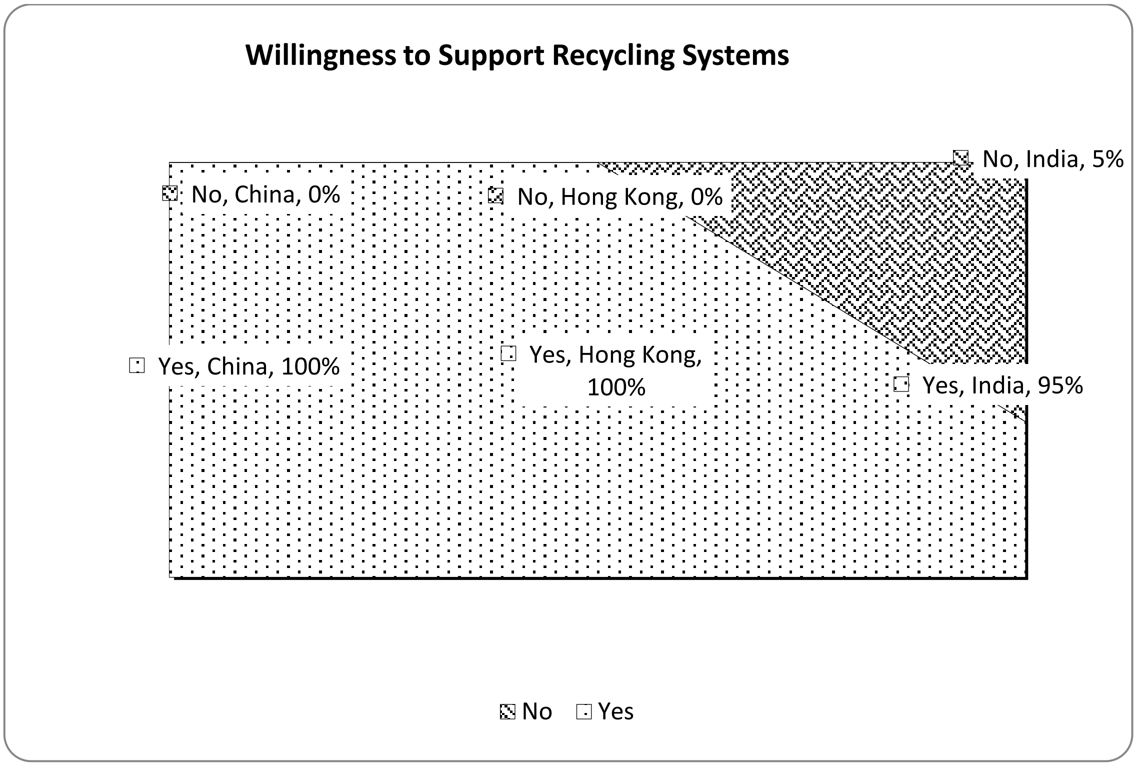


Figure 6-19 Willingness to support recycling systems

Forwarding of used shopping bags to recycling bins provided

This section describes the willingness of respondents to keep shopping bags in the recycling bins provided by the government. The results derived from Mainland China, Hong Kong and India are given in Fig. 6-20. 95% of respondents from Mainland China are willing to place the used bags in bins and those from Hong Kong & India show a 97% willingness in this regard. The remaining 5% of respondents from Mainland

China and 3% of respondents in Hong Kong and India need to be brought into the 'Yes' category by means of educating them on the importance of recycling.

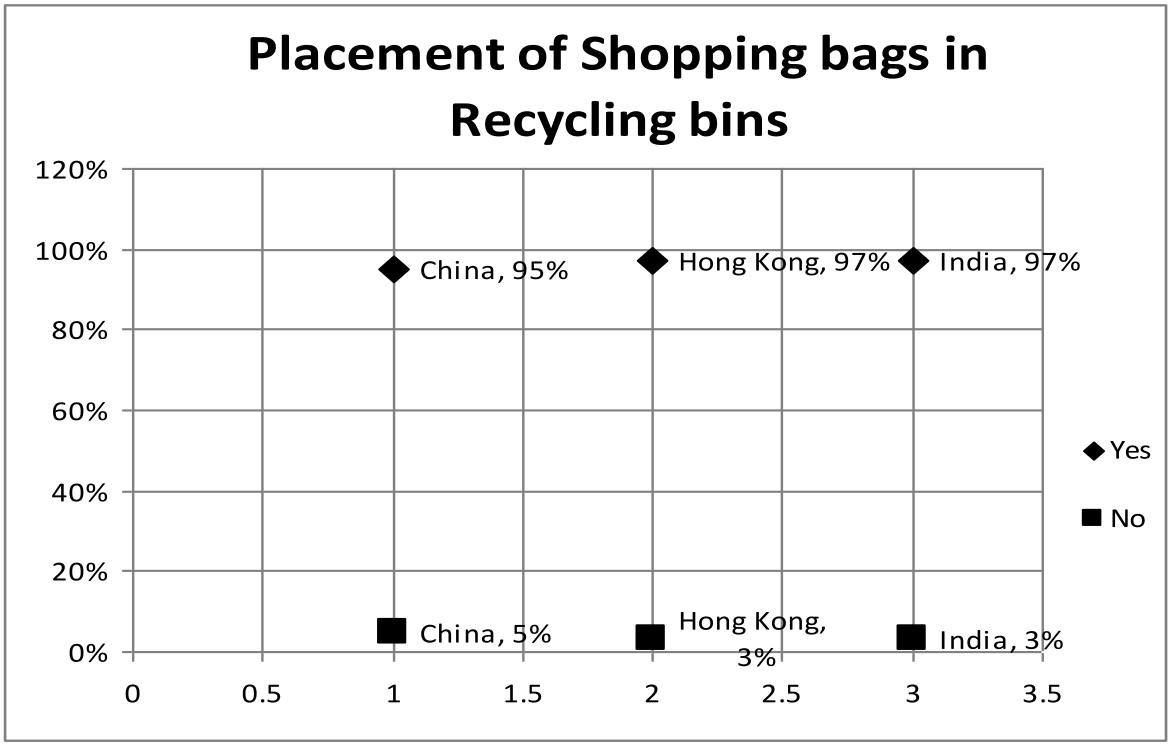


Figure 6-20 Placement of shopping bags in recycling bins

This study reports the usage and disposal behavior of consumers of shopping bags in Mainland China, Hong Kong and India. The results from this survey represent realistically the attitudes and behaviors of young, educated consumers. Hence the results may be employed in life cycle assessment modeling of shopping bags in preference to inappropriate assumptions which do not represent reality. It is the joint venture of individuals and government to work rigorously for optimum usage and disposal scenarios to reduce the environmental impact made by shopping bags. The usage and disposal scenario of different types of shopping bags assume significance over other products, since these bags are professed to be a symbol of the throw-away society. It is imperative and logical to study the eco-impact of shopping bags using survey results which come from the consumers themselves.

The aim of the survey was to comprehend the way in which different groups of consumers would use and dispose of nonwoven and woven bags. Usage and disposal behaviour were defined as how many times people would be likely to reuse different shopping bags, what percentage of shopping bags could be recycled/ sent to the landfill with the existing possibilities of recycling in their own country and what percentage of shopping bags people believed could be reused/recycled/sent to the landfill. The research was also undertaken in order to comprehend the existing recycling options provided by the governments in question and the willingness of people to support the governments' policies to further improve the possibilities of recycling (Muthu et al., 2010a).

6.3. Assessment of functional properties of shopping bags

There are various properties of shopping bags that decide the functionality of the bags and which, in turn, decide consumption behaviour. A series of tests were carried out to assess the functionality of the different shopping bags under consideration in this study. Different shopping bags in various weight ranges were chosen and the details of these can be seen from Table 6-1.

Material	**Low weight[1]**	**Medium weight[2]**	**Heavy weight[3]**
Plastic bags - LDPE	√	√	√
Plastic bags - HDPE	√	√	√
Paper bags	√	√	√

Nonwoven Bags – PP – Sewn Technology	√	√	√
Nonwoven Bags – PP – Thermo-bonded Technology	√	√	√
Nonwoven Bags - PET– Sewn Technology	√	√	√
Nonwoven Bags - PET– Thermo-bonded Technology	√	√	√
Woven - Cotton bags	N.A	√	√

Table 6-1 Samples for evaluation for functional properties

[1-] Equivalent to 40 grams/square meter or whichever is possible in low grams/square meter category.
[2-] Equivalent to 75 grams/square meter or whichever is possible in medium grams/square meter category.
[3-] Equivalent to 100 grams/square meter or whichever is possible in heavy grams/square meter category.

Sample Number	Sample Name	Grams per Sq. metre (GSM)	Weight of one full bag in grams.
1.	Paper 40g	106.9	49.0
2.	Paper 75g	132.4	58.3
3.	Paper 150g	158.7	70.2
4.	Woven Cotton -1	188.1	118.5
5.	Woven Cotton -2	368.3	240.0
6.	HDPE -1	50.8	22.0
7.	HDPE -2	77.2	28.0
8.	HDPE -3	83.5	30.0
9.	LDPE -1	39.5	20.9
10.	LDPE -2	76.0	26.0
11.	LDPE -3	95.2	30.5
12.	PP 40g Sewn	36.7	9.2
13.	PP 75g Sewn	71.6	24.5
14.	PP 100g Sewn	104.6	30.3
15.	PP 40g Thermo	42.2	12.0
16.	PP 75g Thermo	74.3	23.0
17.	PP 100g Thermo	102.9	28.5
18.	PET 40g Sewn	39.0	9.5
19.	PET 75g Sewn	73.9	25.5
20.	PET 100g Sewn	109.9	29.7
21.	PET 40g Thermo	39.7	12.3

22.	PET 75g Thermo	84.9	23.5
23.	PET 100g Thermo	94.9	27.5

Table 6-2 Description of samples (results rounded-off)

Table 6-2 lists the description of various shopping bag samples employed for this study. Table 6-3 shows the various tests conducted for the chosen samples with the relevant standards and the number of samples tested in each category. All tests were carried out under the standard conditions for textile testing.

Serial Number	Test	Testing Standard used	Testing machine used	Testing parameters	No.of.samples tested
1.	Tensile Strength	ASTM D 5034(Grab Test) (ASTM D5034 - 09)	Instron (CRE)	300 mm/min Speed.	5
2.	Tear Strength	ASTM D 1424 & 1922 (ASTM D1922 – 09; ASTM D1424 – 09)	Elmendorf Tearing Tester	Measuring ranges: 200gf, 400gf, 800gf, 1600gf, 3200gf, 6400gf. (Selected according to type of sample)	5
3.	Bursting Strength	ISO 13938-2 (ISO 13938-2:1999)	Pneumatic Tester, Truburst Bursting strength tester (James H Heal & Co.Ltd, England)	Area-7.3 Cm^2; Dia-30.5 mm.	5
6.	Thickness	ASTM D1777 (ASTM D1777 - 96(2007)	SDL fabric thickness tester	Pressure-5gf/cm^2	5
7.	Areal Density	ASTM D3776 (ASTM D3776 / D3776M – 09)	Balance		5
8.	Air Permeability	ISO 9237 (ISO	Air permeability	20 Cm^2 surface area and 100 Pa	5

		9237:1995)	tester	pressure drop.	
9.	Water Vapour Permeability	ASTM E 96 (ASTM E96 / E96M – 10)	As per the standard	As per the standard	3
10.	pH test	ISO 3071 (ISO 3071:2005	Stoppered glass and mechanical shaker and others.	As per the standard	3
11.	Formaldehyde content	ISO 14184-1 (ISO 14184-1:1998)			3
12.	Colour fastness to light	ISO 105 B02 (ISO 105-B02:1994)	Xenon arc lamp apparatus	BWS 4	Tested with BWS
13.	Colour fastness to rubbing	ISO105 X12 (ISO 105-X12:2001)	Crockmeter	As per the standard	Dry and Wet state.
14.	Colour fastness to washing	ISO 105 C 06 -B2 (ISO 105-C06:2010)	Laundrometer	In laundro meter 30 mins , Temp 40 º C, 25 steel balls, 4gpl ECE phosphate +1gpl Sodium. perborate for 150 ml	Tested with Multifibre
15.	Colour fastness to perspiration	ISO105 E 04 (ISO 105-E04:1994)	Test devices as advised by the Standard	4h @ 37º C, Acid and Alkaline Conditions.	Tested with Multifibre
16.	Colour fastness to water	ISO 105 E 01 (ISO 105-E01:1994)			Tested with Multifibre
17.	Fibre Content	ISO 1833-1 (ISO 1833-1:2006)	As per the standard	As per the standard	As per the standard

Table 6-3 Description of tested parameters and methods for functional properties

The average result for each sample in the tests are shown in Tables 6-4 - 6-11 and the individual test results along with standard deviations and co-efficients of variation are listed in Appendix 4. Detailed discussion and the implications of the results are presented in Chapter 8.

Sample No. & Name	Maximum Load (N)	Tensile strain at Maximum Load (%)	Tensile extension at Maximum Load (mm)	Tear Strength (N)
1. Paper 40g	195.9	8.8	6.6	0.6
2. Paper 75g	235.2	6.2	4.6	0.8
3. Paper 150g	272.6	4.3	3.2	1.0
4. Cotton -1	566.0	37.6	28.2	9.8
5. Cotton -2	766.1	38.3	28.7	24.3
6. HDPE -1	100.0	246.0	184.5	6.0
7. HDPE -2	142.3	244.4	183.3	7.6
8. HDPE -3	165.4	281.2	210.9	22.6
9. LDPE -1	60.0	348.5	261.3	0.5
10. LDPE -2	72.7	377.6	283.2	1.1
11 LDPE -3	109.0	371.0	278.2	3.0
12. PP 40g Sewn	141.7	100.4	75.3	25.3
13. PP 75g Sewn	228.2	77.6	58.2	33.8
14. PP 100g Sewn	230.3	55.1	41.3	39.7
15. PP 40g Thermo	127.0	95.3	71. 6	16.3
16. PP 75g Thermo	211.5	87.5	65.6	27.0
17. PP 100g Thermo	249.0	70.4	52.8	45.0
18. PET 40g Sewn	68.4	29.7	22.3	9.4
19. PET 75g Sewn	170.0	52.5	39.4	21.2
20. PET 100g Sewn	244.5	33.7	25.3	24.1
21. PET 40g Thermo	69.4	28.1	21.1	9.6
22. PET 75g Thermo	176.0	54.4	40.8	18.1
23. PET 100g Thermo	182.5	44.6	33.5	21.3

Table 6-4 Tensile and Tear Strength results

Sample No. & Name	Bursting Pressure (PSI)	Height of Inflation (mm)	Time to Burst (s)	Thickness in mm.	Grams/Sq. Meter (GSM
1. Paper 40g	19.1	3.1	7.4	0.08	106.9
2. Paper 75g	21.0	1.7	4.6	0.21	132.4
3. Paper 150g	24.6	1.8	5.2	0.24	158.7
4. Cotton -1	110.4	5.3	22.6	0.54	188.1
5. Cotton -2	125.0	7.5	37.4	0.98	368.3
6. HDPE -1	18.0	9.1	7.8	0.10	50.8
7. HDPE -2	27.1	8.2	8.8	0.14	77.2

8. HDPE -3	33.3	9.0	10.8	0.18	83.5
9. LDPE -1	11.9	10.5	6.0	0.04	39.5
10. LDPE -2	16.3	8.4	10.0	0.09	76.0
11 LDPE -3	21.6	9.5	7.6	0.13	95.2
12. PP 40g Sewn	28.1	13.1	9.2	0.35	36.7
13. PP 75g Sewn	42.4	12.5	19.2	0.46	71.6
14. PP 100g Sewn	70.0	11.0	17.0	0.61	104.6
15. PP 40g Thermo	29.4	12.4	9.4	0.35	42.2
16. PP 75g Thermo	44.1	12.0	13.8	0.55	74.3
17. PP 100g Thermo	59.3	12.4	16.8	0.68	103.0
18. PET 40g Sewn	27.2	6.7	8.0	0.30	39.0
19. PET 75g Sewn	55.1	8.3	15.0	0.50	73.9
20. PET 100g Sewn	67.0	7.5	17.6	0.55	109.9
21. PET 40g Thermo	22.7	6.4	11.4	0.33	39.7
22. PET 75g Thermo	56.4	8.7	18.8	0.52	84.8
23. PET 100g Thermo	60.2	7.7	18.4	0.56	94.8

Table 6-5 Bursting strength, thickness and GSM results (results rounded-off)

Sample No. & Name	Air Permeability (mm/s)	Water Vapour Permeability [g/m^2.day]^	pH	Formaldehyde Content-mg/kg	Fibre Composition
1. Paper 40g	0	680.1	6.92	8.87 PPM *	100% Paper
2. Paper 75g	0	617.2	6.87	8.91 PPM *	100% Paper
3. Paper 150g	0	669.1	6.84	8.67 PPM *	100% Paper
4. Cotton -1	166	936.3	6.89	14.06 PPM *	100% Cotton
5. Cotton -2	42	948.4	Body 9.12 lining 6.20	10.87 PPM *	Cotton/ Poly 52.5/47.5 (lining: 100% cotton)
6. HDPE -1	0	83.9	6.82	8.48 PPM *	100% Polyethylene

7. HDPE -2	0	17.7	6.98	8.71 PPM *	100% Polyethylene
8. HDPE -3	0	14.3	6.94	8.64 PPM *	100% Polyethylene
9. LDPE -1	0	33.1	6.87	8.82 PPM *	100% Polyethylene
10. LDPE -2	0	27.6	6.78	8.68 PPM *	100% Polyethylene
11 LDPE -3	0	25.4	6.91	8.92 PPM *	100% Polyethylene
12. PP 40g Sewn	789	983.8	6.74	8.78 PPM*	100% Polypropylene
13. PP 75g Sewn	789	955.0	6.69	8.68PPM *	100% Polypropylene
14. PP 100g Sewn	632	908.7	7.00	5.86PPM *	100% Polypropylene
15. PP 40g Thermo	789	1003.6	6.68	8.70PPM *	100% Polypropylene
16. PP 75g Thermo	789	936.3	6.62	8.74PPM *	100% Polypropylene
17. PP 100g Thermo	570	947.3	6.64	8.74PPM *	100% Polypropylene
18. PET 40g Sewn	789	928.5	6.84	8.68PPM *	100% Polyester
19. PET 75g Sewn	789	936.3	6.92	8.62PPM *	100% Polyester
20. PET 100g Sewn	564	875.5	6.86	8.64PPM *	100% Polyester
21. PET 40g Thermo	789	922.0	6.90	8.60PPM *	100% Polyester
22. PET 75g Thermo	746	956.1	6.86	8.64PPM *	100% Polyester
23. PET 100g Thermo	631	991.5	6.88	8.59PPM *	100% Polyester

*not detected

Table 6-6 Air & Water Permeability, pH, Formaldehyde and Fibre Content results (results rounded-off)

Sample No. & Name	Light Fastness (BWS 4)	Dry Rubbing Fastness	Wet Rubbing Fastness
1. Paper 40g	4	N/A	N/A
2. Paper 75g	4	N/A	N/A
3. Paper 150g	4	N/A	N/A

4. Cotton -1	4	4/5	4
5. Cotton -2	4	Body 3/4; Lining 4/5	Body 2/3; Lining 4/5
6. HDPE -1	4	N/A	N/A
7. HDPE -2	4	N/A	N/A
8. HDPE -3	4	N/A	N/A
9. LDPE -1	4	N/A	N/A
10. LDPE -2	4	N/A	N/A
11 LDPE -3	4	N/A	N/A
12. PP 40g Sewn	4	4/5	4/5
13. PP 75g Sewn	4	4/5	4/5
14. PP 100g Sewn	4	4/5	4/5
15. PP 40g Thermo	4	4/5	4/5
16. PP 75g Thermo	4	4/5	4/5
17. PP 100g Thermo	4	4/5	4/5
18. PET 40g Sewn	4	N/A	N/A
19. PET 75g Sewn	4	N/A	N/A
20. PET 100g Sewn	4	N/A	N/A
21. PET 40g Thermo	4	N/A	N/A
22. PET 75g Thermo	4	N/A	N/A
23. PET 100g Thermo	4	N/A	N/A

Table 6-7 Colour fastness to light and rubbing results

Sample No. & Name	Washing Fastness grade						
	Acetate	Cotton	Nylon	Polyester	Acrylic	Wool	Overall rating
1. Paper 40g	4	4	4-5	4	4-5	4	4
2. Paper 75g	4	4-5	4	4	4	4-5	4
3. Paper 150g	4	4-5	4-5	4	4	4-5	4
4. Cotton -1	4-5	4	4	4-5	4-5	4-5	4
5. Cotton -2	4-5	4-5	4-5	4-5	4-5	4-5	4
6. HDPE -1	4-5	4	4	4-5	4-5	4-5	4
7. HDPE -2	4	4-5	4-5	4	4	4-5	4
8. HDPE -3	4	4-5	4	4	4	4-5	4
9. LDPE -1	4	4	4-5	4	4-5	4	4
10. LDPE -2	4-5	4-5	4	4	4-5	4	4
11 LDPE -3	4	4-5	4	4	4	4-5	4
12. PP 40g Sewn	4	4-5	4-5	4	4	4-5	4
13. PP 75g Sewn	4-5	4	4-5	4	4-5	4-5	4
14. PP 100g Sewn	4-5	4-5	4-5	4	4	4	4

15. PP 40g Thermo	4-5	4	4-5	4	4-5	4-5	4
16. PP 75g Thermo	4	4-5	4-5	4	4	4-5	4
17. PP 100g Thermo	4-5	4-5	4-5	4	4	4	4
18. PET 40g Sewn	4-5	4	4-5	4	4-5	4-5	4
19. PET 75g Sewn	4	4	4-5	4	4-5	4	4
20. PET 100g Sewn	4-5	4-5	4-5	4	4	4	4
21. PET 40g Thermo	4-5	4	4-5	4	4-5	4-5	4
22. PET 75g Thermo	4	4	4-5	4	4-5	4	4
23. PET 100g Thermo	4-5	4	4-5	4	4-5	4-5	4

Table 6-8 Colour fastness to washing results

Sample No. & Name	Acid Perspiration Fastness grade						
	Acetate	Cotton	Nylon	Polyester	Acrylic	Wool	Overall rating
1. Paper 40g	4	4-5	4-5	4	4	4-5	4
2. Paper 75g	4	4	4-5	4	4-5	4	4
3. Paper 150g	4-5	4	4	4-5	4-5	4-5	4
4. Cotton -1	4	4-5	4-5	4	4	4-5	4
5. Cotton -2	4-5	4-5	4-5	4-5	4-5	4-5	4
6. HDPE -1	4-5	4	4	4-5	4-5	4-5	4
7. HDPE -2	4	4	4-5	4	4-5	4	4
8. HDPE -3	4-5	4	4	4-5	4-5	4-5	4
9. LDPE -1	4	4-5	4	4	4	4-5	4
10. LDPE -2	4-5	4-5	4	4	4-5	4	4
11 LDPE -3	4	4	4-5	4	4-5	4	4
12. PP 40g Sewn	4-5	4-5	4	4	4	4-5	4
13. PP 75g Sewn	4	4-5	4-5	4	4	4-5	4
14. PP 100g Sewn	4-5	4	4-5	4	4-5	4-5	4
15. PP 40g Thermo	4	4	4-5	4	4-5	4	4
16. PP 75g Thermo	4-5	4	4-5	4	4-5	4-5	4

17. PP 100g Thermo	4-5	4-5	4-5	4	4	4	4
18. PET 40g Sewn	4-5	4	4-5	4	4-5	4-5	4
19. PET 75g Sewn	4	4	4-5	4	4-5	4	4
20. PET 100g Sewn	4-5	4	4-5	4	4-5	4-5	4
21. PET 40g Thermo	4-5	4-5	4-5	4	4	4	4
22. PET 75g Thermo	4	4	4-5	4	4-5	4-5	4
23. PET 100g Thermo	4	4-5	4-5	4	4-5	4-5	4

Table 6-9 Colour fastness to perspiration results – Acid

Sample No. & Name	Alkali Perspiration Fastness grade						
	Acetate	Cotton	Nylon	Polyester	Acrylic	Wool	Overall rating
1. Paper 40g	4	4	4	4	4	4-5	4
2. Paper 75g	4-5	4	4	4-5	4-5	4-5	4
3. Paper 150g	4	4	4-5	4	4-5	4	4
4. Cotton -1	4	4	4	4	4	4-5	4
5. Cotton -2	4-5	4-5	4-5	4-5	4-5	4-5	4
6. HDPE -1	4	4-5	4	4	4	4-5	4
7. HDPE -2	4-5	4-5	4	4	4-5	4	4
8. HDPE -3	4	4	4-5	4	4-5	4	4
9. LDPE -1	4-5	4-5	4	4	4-5	4	4
10. LDPE -2	4	4-5	4	4	4	4-5	4
11 LDPE -3	4	4	4-5	4	4-5	4	4
12. PP 40g Sewn	4-5	4-5	4	4	4	4-5	4
13. PP 75g Sewn	4	4-5	4-5	4	4	4-5	4
14. PP 100g Sewn	4-5	4-5	4	4	4-5	4	4
15. PP 40g Thermo	4	4-5	4	4	4	4-5	4
16. PP 75g Thermo	4-5	4-5	4	4	4-5	4	4
17. PP 100g Thermo	4-5	4-5	4-5	4	4	4	4
18. PET 40g Sewn	4	4-5	4-5	4	4	4-5	4

19. PET 75g Sewn	4-5	4-5	4	4	4-5	4	4
20. PET 100g Sewn	4	4-5	4	4	4	4-5	4
21. PET 40g Thermo	4	4-5	4-5	4	4	4-5	4
22. PET 75g Thermo	4-5	4-5	4	4	4-5	4	4
23. PET 100g Thermo	4	4-5	4	4	4	4-5	4

Table 6-10 Colour fastness to perspiration results – Alkali

Sample No. & Name	Water Fastness grade						
	Acetate	Cotton	Nylon	Polyester	Acrylic	Wool	Overall rating
1. Paper 40g	4-5	4	4-5	4-5	4-5	4-5	4
2. Paper 75g	4	4	4-5	4	4-5	4	4
3. Paper 150g	4	4-5	4	4	4	4-5	4
4. Cotton -1	4-5	4	4	4-5	4-5	4-5	4
5. Cotton -2	4-5	4-5	4-5	4-5	4-5	4-5	4
6. HDPE -1	4-5	4	4	4-5	4-5	4-5	4
7. HDPE -2	4	4	4-5	4	4-5	4	4
8. HDPE -3	4-5	4-5	4	4	4-5	4	4
9. LDPE -1	4-5	4-5	4	4	4-5	4	4
10. LDPE -2	4	4	4-5	4	4-5	4	4
11 LDPE -3	4	4-5	4	4	4	4-5	4
12. PP 40g Sewn	4-5	4-5	4	4	4-5	4	4
13. PP 75g Sewn	4	4-5	4	4	4	4-5	4
14. PP 100g Sewn	4	4-5	4	4	4	4-5	4
15. PP 40g Thermo	4	4	4-5	4	4-5	4	4
16. PP 75g Thermo	4	4-5	4	4	4	4-5	4
17. PP 100g Thermo	4	4-5	4	4	4	4-5	4
18. PET 40g Sewn	4-5	4-5	4	4	4-5	4	4
19. PET 75g Sewn	4	4	4-5	4	4-5	4	4
20. PET 100g Sewn	4-5	4-5	4	4	4-5	4	4

21. PET 40g Thermo	4	4-5	4	4	4	4-5	4
22. PET 75g Thermo	4-5	4-5	4	4	4-5	4	4
23. PET 100g Thermo	4	4-5	4-5	4	4	4-5	4

Table 6-11 Colour fastness to water results

6.4. Assessment of Eco-functional properties of shopping bags: Development of a novel Eco-functional tester

Along with the functional properties listed in section 6.2, there are eco-functional properties which influence consumption behavior. This research work discusses the development of a novel test instrument to quantify the eco-functional properties of various shopping bags. One of the main properties, which is located at the interface of ecological and functional properties, is the reusability of shopping bags. Other relevant properties include impact strength and weight-holding capacity of a shopping bag. The developed tester can be used to assess these three properties (reusability, impact strength and weight-holding capacity) of any type of shopping bag. This study discusses the concept and development of an eco-functional tester for shopping bags. It also reports test results of the reusability, impact strength and weight-holding capacity of different types of shopping bags. Reusability and impact strength are expressed by two variants: absolute maximum capacity and comparative maximum capacity.

Shopping bags made out of any material, such as polyethylene, paper, cotton, polypropylene, jute, nylon, etc. and manufactured by any technique, nonwoven, woven, knitting technologies, plastic and paper bag processes, and so on, are primarily expected to be used many times. Here the discussion is confined to grocery bags used in super markets. The primary functions expected of a shopping bag are: a) How much time and how much weight, a shopping bag can sustain; b) How many times can it be reused to carry a specified amount of weight, as per the claim of the manufacturer or in general according to the capacity of the bag; c) How much impact can it withstand. These are the major functions expected of a shopping bag and these functions can determine their functionality; in other words, they decide the useful life time of a shopping bag. Since these properties also decide the ecological characteristics of a shopping bag, I term them "Eco-functional Properties".

In recent years, the 3Rs has become a buzz term heard repeatedly worldwide: Reuse, Recycle and Reduce. Of these terms, the first, i.e. Reuse determines both the ecological and functional properties of a shopping bag. If a shopping bag is reused many times, due to its added functionality, its ecological benefits are included in terms of avoiding/postponing the depletion of resources to manufacture another bag. Preventing the bag being recycled or sent to landfill earlier also limits ecological damage. Hence properties such as, reusability, weight-holding capacity and impact strength decide the eco-functional properties of shopping bags.

It is important to quantify these properties to decide the eco-functional characteristics of a shopping bag. There are no instruments available currently that are able to assess eco-functional characteristics scientifically. The kind of instrument which can test the reusability of a shopping bag will aid both manufacturers and customers. Above all, such an instrument will benefit the whole society in terms of environmental protection.

Life Cycle Assessment (LCA) studies deal with the quantification of the environmental impact made by any product/process in its useful time. Among the different phases of LCA, the end-of-life phase of any product deserves close attention. One of the parameters used in this phase is reuse, i.e. how many times a product can be reused. To date, there is no scientific instrument reported in the literature that quantifies the reusability of different shopping bags. The value of reusability can be directly utilized for LCA calculations. Other functions derived from this instrument are equally important, since they decide the useful life time of shopping bag and they assist the LCA practitioner to decide the functional unit of the study. This unit is the base of any LCA study and upon it comparisons are made.

As indicated earlier, a large number of studies have been conducted to investigate the LCA of various shopping bags and included an end-of-life assumption in the modelling. Other studies reported the gathering and use of real data arising on recycling/reuse/landfill options from consumers of shopping bags (Muthu et al., a, 2012a, 2010a, and 2011). However, with the aid of the developed instrument, there is no need to assume the end-of-life values at least for the reusability function, which is one of the crucial considerations in end-of-life scenarios. Also with the aid of the developed instrument, it is possible to compare the actual reuse values of shopping bags derived from the developed instrument with the values derived from surveys of consumers. The results all suggest that consumers modify their behaviour to prevent the environmental impact arising from the early disposal of shopping bags before their actual end-of-life.

Based on the circumstances described above, a specific tester was designed to ascertain the eco-functional properties of shopping bags. The present instrument was developed to quantify both the ecological and functional properties of any kind of shopping bag. As stated earlier, the following properties of shopping bags will be assessed by this new instrument:

1.Reusability – No. of. times a bag can be reused;

2.Holding Capacity of a bag;

3.Impact Strength – Testing of strength when a sudden impact is applied to a bag.

6.4.1. Assessment of eco-functional properties

The working principles of the developed instrument are described as below for the three functions discussed above:

1. Reusability

This property will be tested by clamping the handle of the bag into the holding mechanism of the instrument and maintaining a designated load on the bag and subjecting it to a to and fro motion till the bag is broken.

2. Holding Capacity of a bag

This will be tested again by clamping the handle of the bag into the holding mechanism and maintaining the particular load onto the bag while keeping it in a still state until it is broken. Alternatively, the bag is held for a certain period of time say 1 minute or 2 minutes or more.

3. Impact Strength

This will be tested by dropping designated weights, say 1 kg, 2kg...5kg, etc into the bag from a certain distance, thereby creating a progressive impact force that tears the shopping bag.

6.4.2. Working principle of the instrument

As discussed earlier in this chapter, the present invention provides the development of a new instrument to quantify the eco-functional properties of various shopping bags. Fig.6-21 illustrates the working principle of the developed instrument.

The instrument can cover one meter of movement in one cycle and it is operated at 10cm/s speed. The whole instrument weighs around 200 kilograms, needs 0.6 MPA air source requirements and can bear a maximum load of 40 kilograms. The instrument is equipped with a touch screen to input both the parameters of the shopping bag and those of the instrument. A PC interface is also connected to operate the machine through a computer. With the aid of this PC interface, it is possible to obtain the results of each test in a graphical format and also to save the data for future uses. Data can be saved in terms of the graphical format and also in MS- Excel format.

The following data can be acquired from the instrument through PLC:

I. The number of times a bag can be reused;

II. Duration of weight holding;

III. Weight held by a bag;

IV. Condition of bag and position of break.

This machine is equipped with 18 sensors, of which 16 are functioning and two are inactive. There are 6 load sensors, of which four sense the load carried by a bag. There is a holding mechanism on which these sensors are arranged. Information regarding the load carried by these four sensors will be transferred to the PC and saved in Excel format and displayed as a graph. In case of a failure of the handles of a bag, one of the four load sensors will stop the machine due to the drop in the load. If there is a break in the body of the bag, the drop safety sensor shown in Fig. 6-21 will stop the machine.

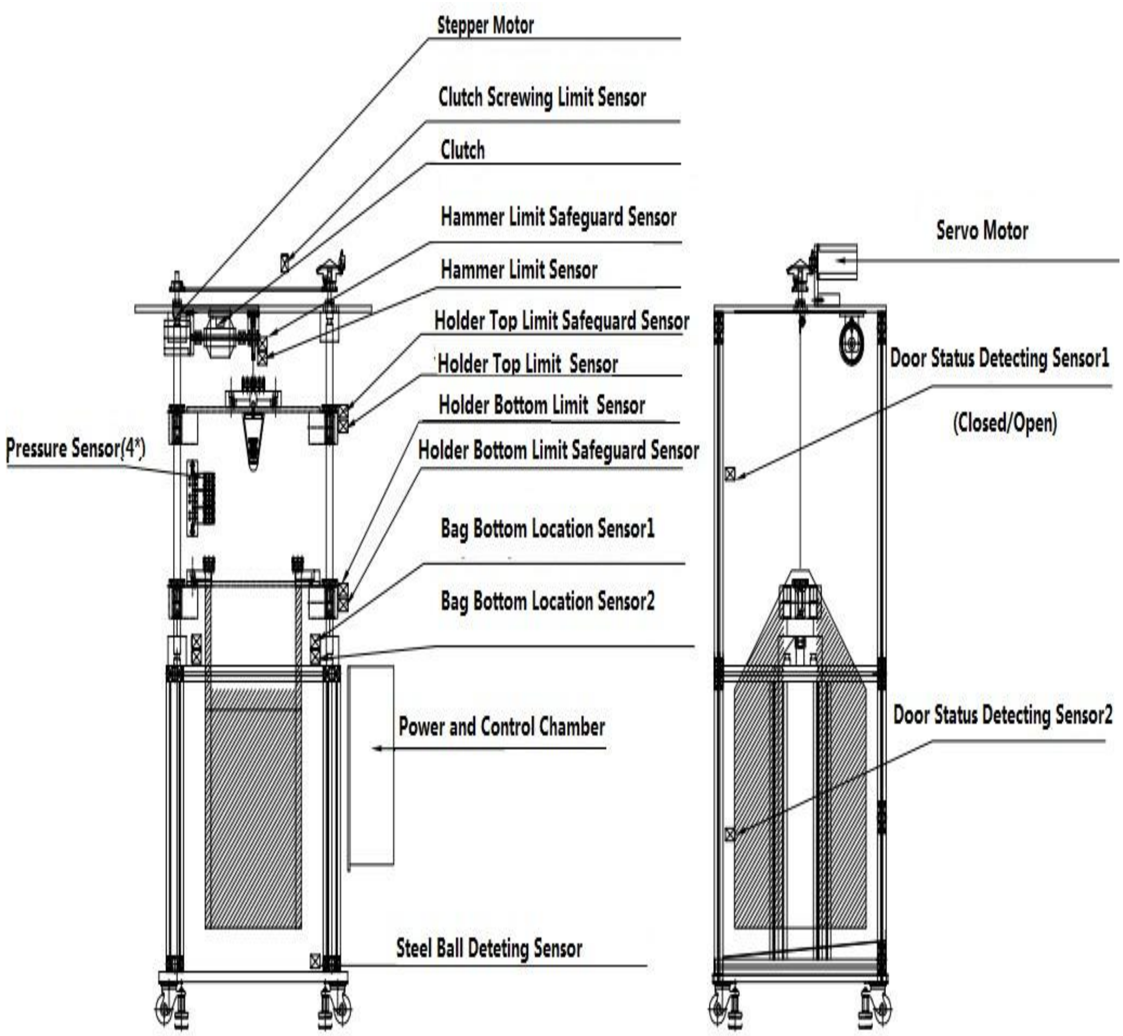


Figure 6-21 Description of Eco-functional Tester

Steel balls of different sizes are used as weights. In case of failure of a bag, steel balls drop down and the broken balls activate the bag wear ball sensor at the bottom of the machine and stop the machine. So, in case of failure, either of these mechanisms will deactivate the machine.

For testing the reusability function, a bag is mounted on the holding mechanism and the designated weight is placed in the bag. The whole mechanism will then move to and fro to complete one cycle. For testing weight-holding capacity, the same procedure is followed except for the to and fro motion. With the PC interface and the touch display screen, it is possible to select the test method and also to adjust the speed of the machine by altering the frequency.

To test the impact strength, in addition to the procedure for weight-holding capacity, a hammer is designed in two ball sizes and weights (38 mm diameter, weight 2 kilograms and 50 mm diameter, weight 3 kilograms). The hammer is mounted on a separate mechanism as shown in Fig.6-21. To maintain the uniform mass falling distance irrespective of the position of the shopping bag, two sensors are located at the bottom of the machine (Fig.6-21) to sense the position of the bag and to control the distance from which the hammer falls. This is very important for the impact test, since distance is one of the crucial factors to determine the impact force (Impact Force= Mass * Distance).

To ensure the safety of personnel, there are two sensors located at the machine door and there is an emergency stop switch also provided which stops the machine immediately in case of any emergency (Li et al.,a).

6.4.3. Indices definition

The derived parameters from each test are given below:

1. ***Reusability:***

This parameter will be determined by assessing the number of times a bag can be reused with the designated load. It will be expressed by the number of times the maximum load is carried by a bag of a specific unit weight (maximum number of times with the maximum load / unit weight of bag).

2. ***Holding capacity of a bag:***

This parameter will be expressed in terms of how much time a bag can hold the claimed load without failure, expressed by its corresponding unit weight (maximum amount of time with the maximum load / unit weight of bag).

3. ***Impact strength:***

This will be expressed in terms of the maximum weight a shopping bag can bear when an impact force is exerted, expressed by its unit weight (maximum no. of cycles a big withstands with a certain impact load / unit weight of bag).

Shopping bags made from different raw materials and with different specifications will bear different units of load. Such materials cannot be compared on one uniform platform if they are being tested to assess maximum capacity alone. Hence, reusability and impact strength are expressed by both absolute maximum capacity and comparative maximum capacity.

It is possible to input various parameters of shopping bags such as weight, length, width, thickness and also handle parameters such as length, width and thickness. Testing parameters such as type of test, amount of load, number of cycles and testing time for weight- holding capacity can also be input.

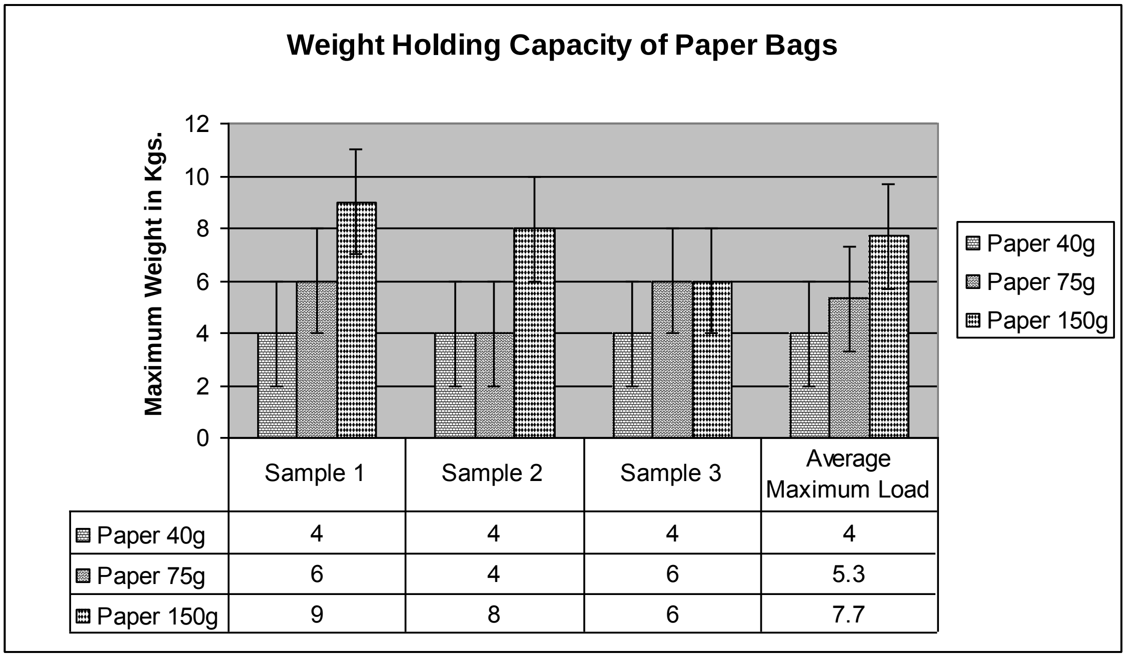
6.4.4. Experimentation of eco-functional properties of shopping bags

To test the eco-functional properties of shopping bags by the developed instrument, different types of shopping bags were chosen as discussed in section 6.2. Table 6-2 provides descriptions of the shopping bags chosen for testing. As indicated in Table 6-2, a total of 23 samples were tested for three functions.

6.4.5. Results and discussion

1. Weight-holding capacity test

In this test, all the shopping bag samples under consideration for the current research were tested for their maximum weight-holding capacity for 5 minutes. During the 5-minute period, samples were observed for hole formation, crack formation, propagation of tear/break in any part of the sample and failure of handles and body. Occurrence of any of these phenomena meant that a particular sample was treated as a failure of the sample to meet the requirements of this test. A sample withstanding the designated load for 5 minutes without exhibiting any failure phenomena was treated as meeting the test's requirements. For each sample, 3 specimens were tested. Three individual readings were taken and the averages of these three readings with error bars are reported. Each sample was tested from the lowest level of weight to the maximum weight by gradually adding weights of 1 kg. and the results at the maximum load for various shopping bags are reported in Figs.6-22 - 6-29. Figs. 6-22 – 6-29 illustrate the weight-holding capacity results for paper bags.



	Sample 1	Sample 2	Sample 3	Average Maximum Load
Paper 40g	4	4	4	4
Paper 75g	6	4	6	5.3
Paper 150g	9	8	6	7.7

Figure 6-22 Weight-holding capacity of paper bags

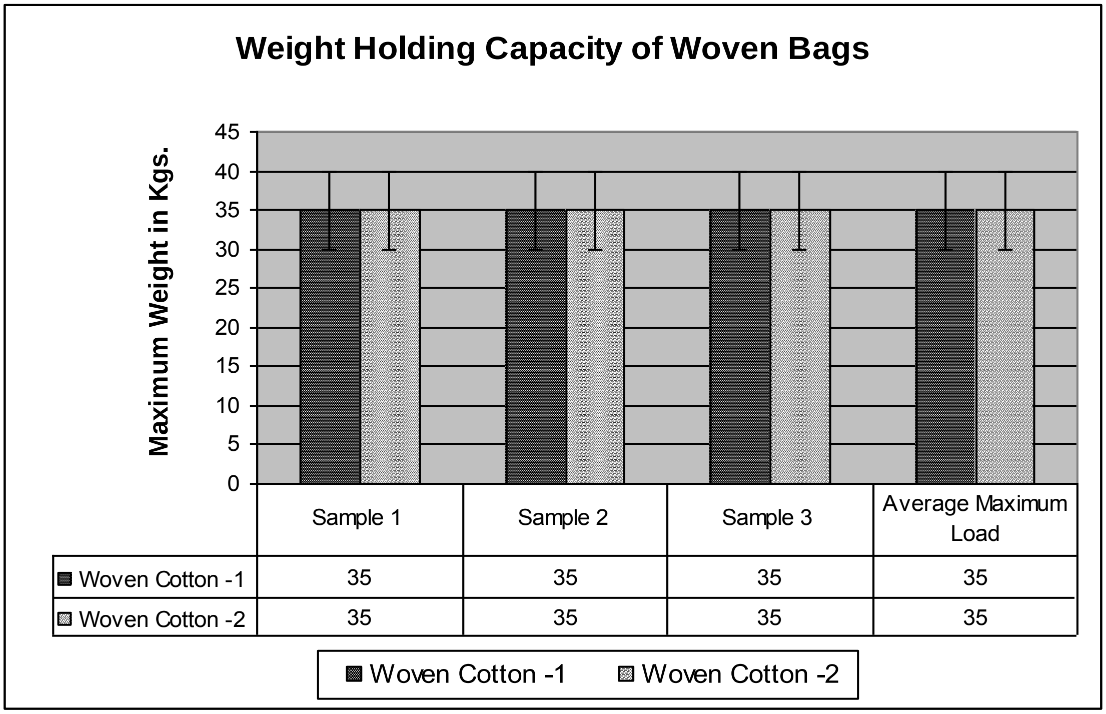


Figure 6-23 Weight-holding capacity of woven bags

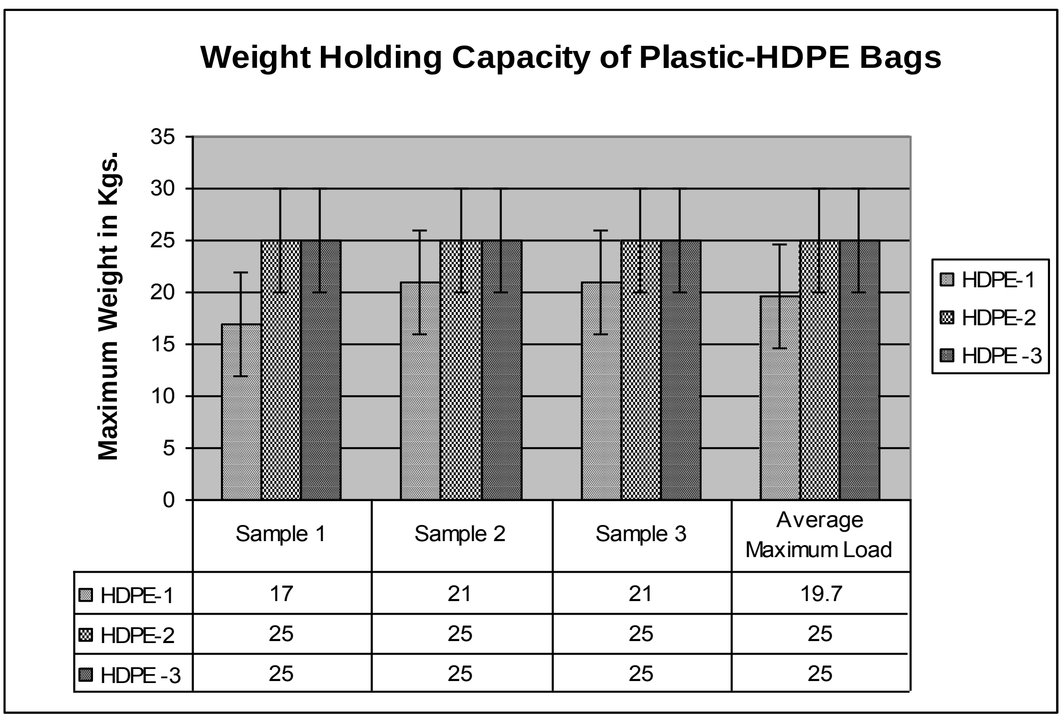
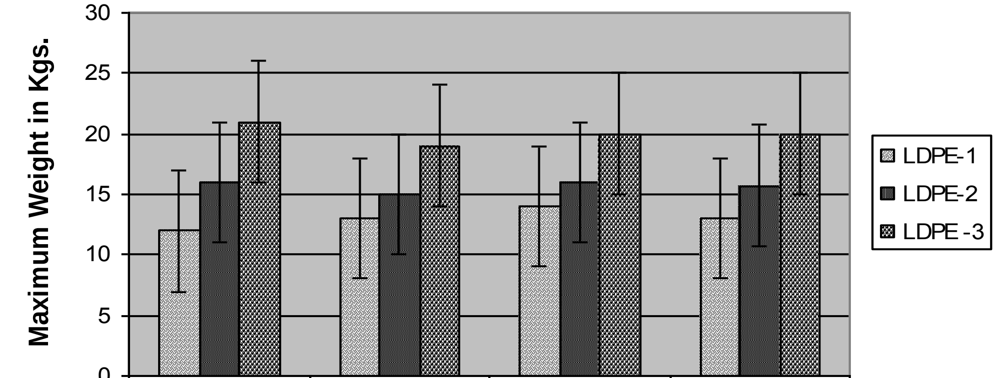
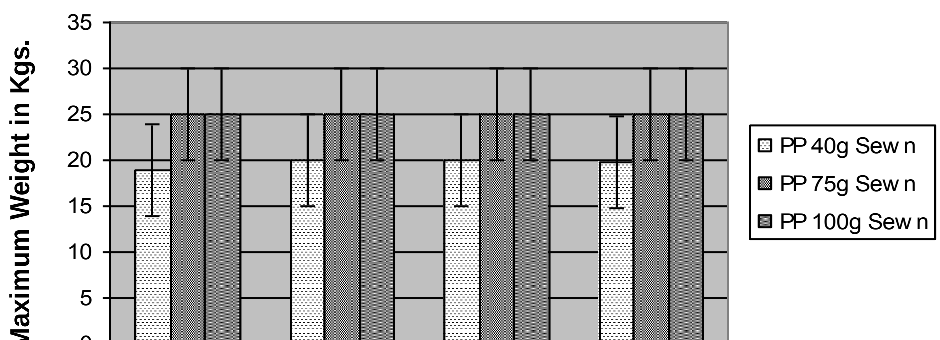


Figure 6-24 Weight-holding capacity of plastic (HDPE) bags



	Sample 1	Sample 2	Sample 3	Average Maximum Load
LDPE-1	12	13	14	13
LDPE-2	16	15	16	15.7
LDPE -3	21	19	20	20

Figure 6-25 Weight-holding capacity of plastic (LDPE) bags



	Sample 1	Sample 2	Sample 3	Average Maximum
PP 40g Sew n	19	20	20	19.7
PP 75g Sew n	25	25	25	25
PP 100g Sew n	25	25	25	25

Figure 6-26 Weight-holding capacity of nonwoven bags – PP sewn

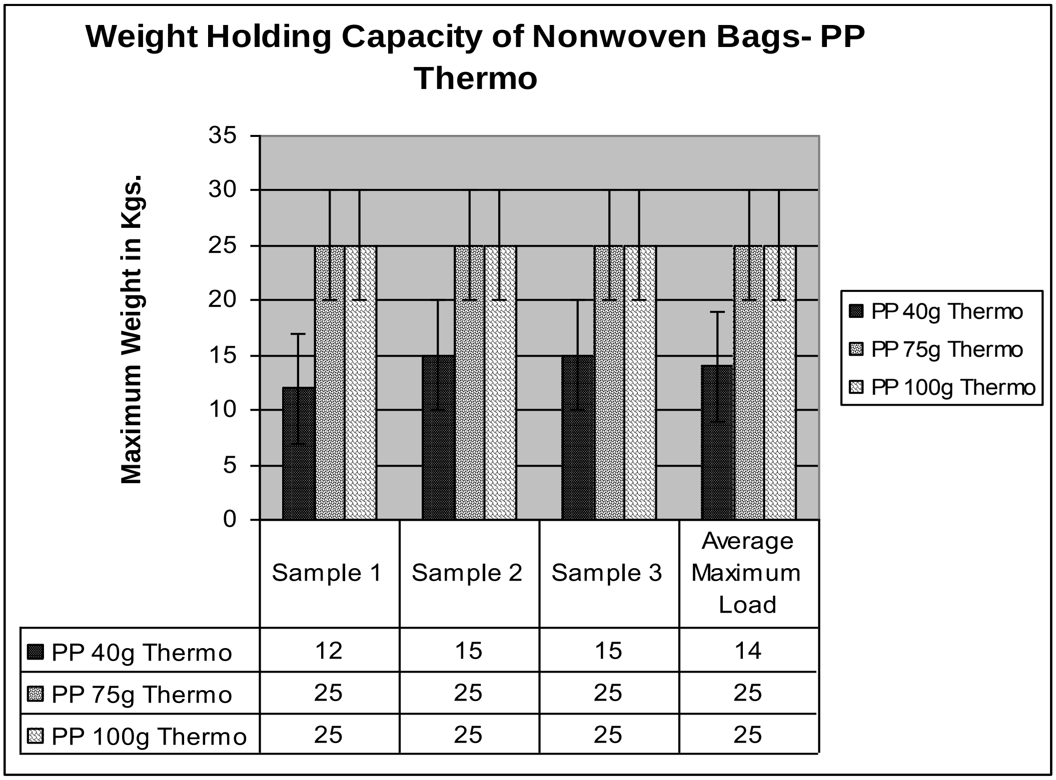


Figure 6-27 Weight-holding capacity of nonwoven bags – PP thermo

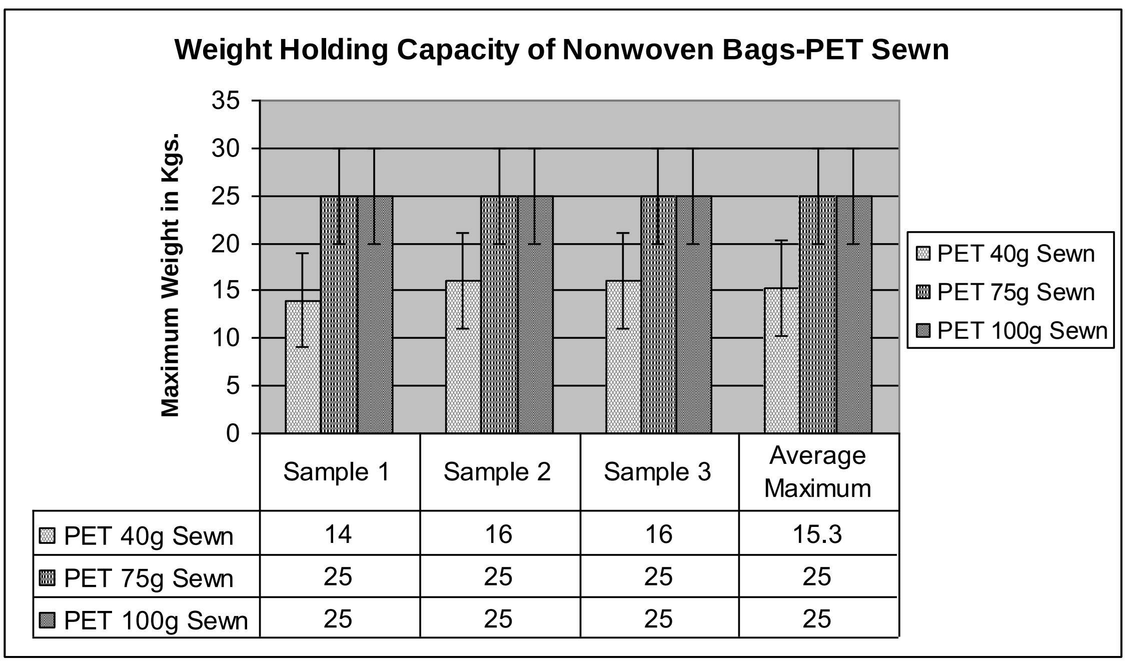
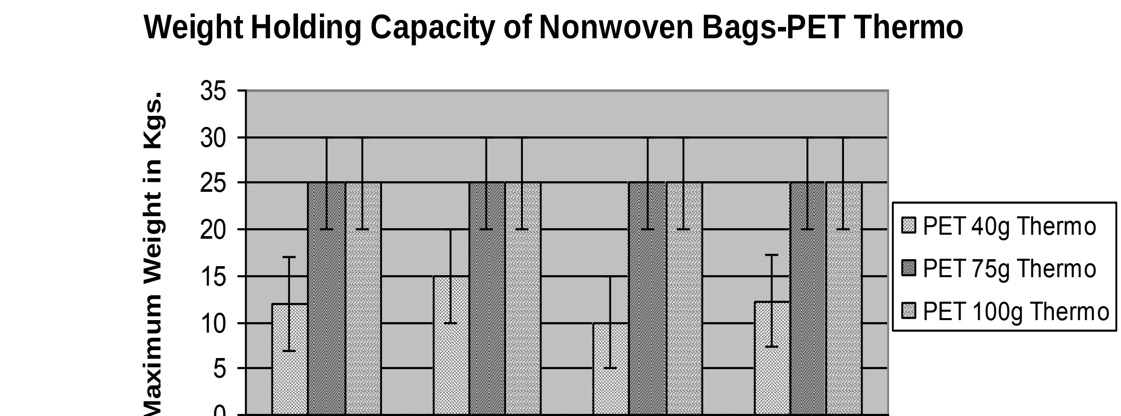


Figure 6-28 Weight-holding capacity of nonwoven bags – PET sewn



	Sample 1	Sample 2	Sample 3	Average Maximum
PET 40g Thermo	12	15	10	12.3
PET 75g Thermo	25	25	25	25
PET 100g Thermo	25	25	25	25

Figure 6-29 Weight-holding capacity of nonwoven bags – PET thermo

As seen from Figs.6-22-6-29, woven bags have the maximum weight-holding capacity in the list. They can withstand up to a maximum of 35 kgs. Paper bags have the lowest weight-holding capacity among the experimental samples. Even a heavy weight paper bag could only hold a maximum 8 kgs.for 5 minutes.

In this test, an attempt was made to assess the maximum load a bag can withstand, irrespective of practical factors. The aim of this test is to consider the maximum amount of load a bag can withstand for 5 minutes. So, maximum load was maintained and tested for 5 minutes.

Regarding the plastic bags (LDPE and HDPE of various unit weights under question of this study) recorded a maximum of 20 and 25 kgs. respectively. Thermo-bonded nonwoven bags made from PET of 40 GSM endured a maximum of 12.3 kgs. and withstood around 15 kgs., if sewn. On the other hand, thermo-bonded bags of the same weight made from PP withstood a maximum of 14 kgs. and survived at 20 kgs. if sewn.

As regards nonwoven bags of 75 and 100 GSM, all survived a maximum load of 25 kgs., which is the maximum load they can hold for their sizes.

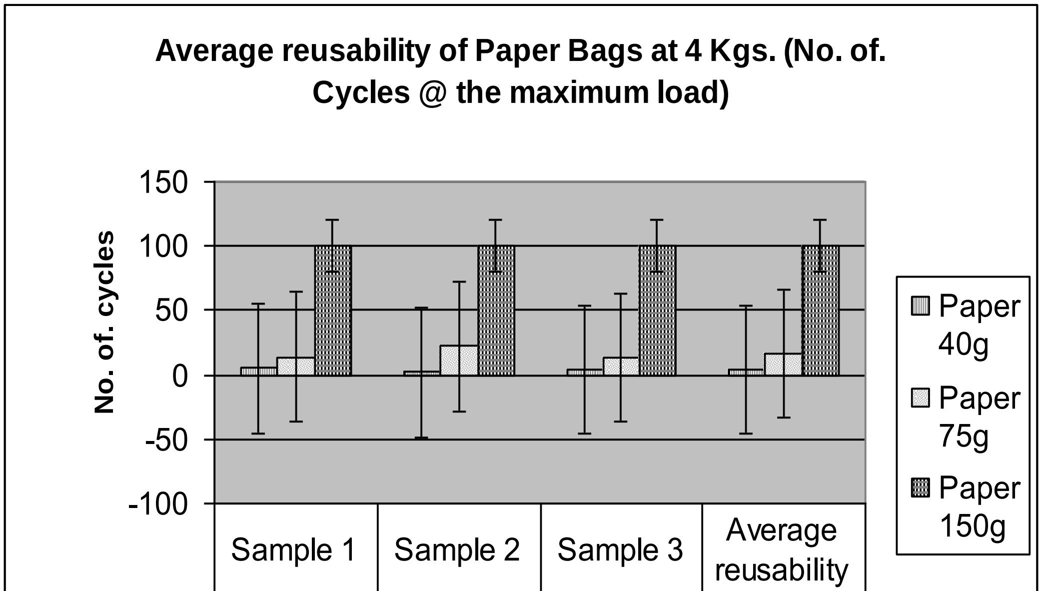
2. Reusability of shopping bags

a. Absolute Maximum Capacity

To assess the reusability of shopping bags under discussion, a fixed number of 100 cycles was chosen. Keeping the number of cycles constant, this test was conducted at varying the weights to determine the maximum reusability of a bag at different weight levels to establish the maximum weight carrying capacity of the bag.

Since paper bags were assumed to be the weakest of all samples considered in this study, they were chosen with the minimum weight of 4 kilograms and were tested to fulfill 100 cycles. The results of the tests of reusability of paper bags are shown in Fig.6-30. It can be seen from Fig.6-30 that heavy weight paper bags can withstand 100 cycles at 4 kilograms of load.

Regarding cotton woven samples, their maximum capacity is 35 kilograms, but in fact, they can hold a greater weight. Since, however, an individual will find it difficult to carry more than 35 kgs. many times, a maximum of 35 kgs.was chosen. They were tested at various load levels from 10 kgs. to 35 kgs. and the results at the maximum load are reported in Fig.6-31.



	Sample 1	Sample 2	Sample 3	Average reusability
Paper 40g	5	2	4	3.7
Paper 75g	14	22	13	16.3
Paper 150g	100	100	100	100

Figure 6-30 Reusability results of paper bags

In this test, the maximum load a bag can bear was decided by considering many factors such as how much load a bag can comfortably tolerate without it being stretched beyond its limit and at the maximum load, a consumer can carry the bag. In this test, the primary objective is to test the number of times a bag can be reused at its maximum possible load capacity.

As regards HDPE and LDPE, their maximum capacity is 15 kilograms. They were tested at both 10 and 15 kilograms to fulfill 100 cycles. The results at the maximum load are reported in Fig.6-32. Medium and heavy weight HDPE and heavy weight LDPE can bear the maximum designated load, as can be seen from Fig.6-32.

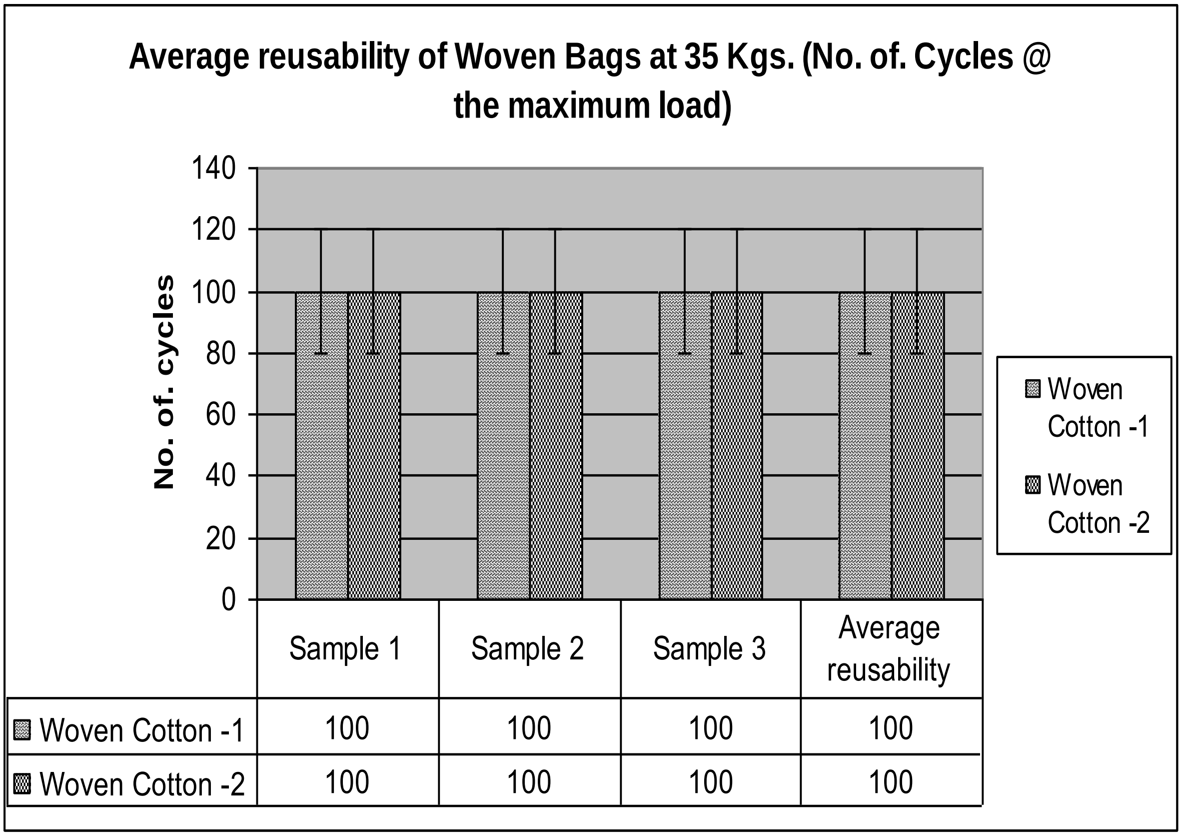
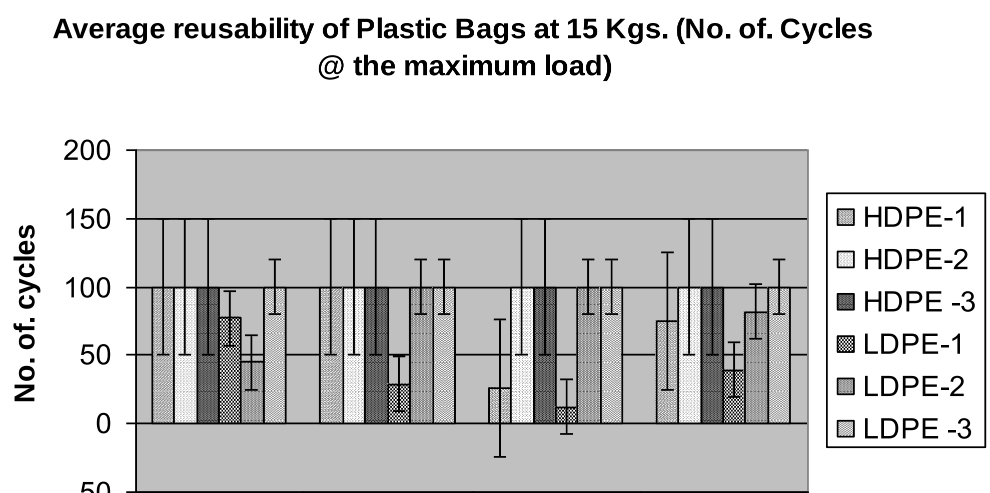


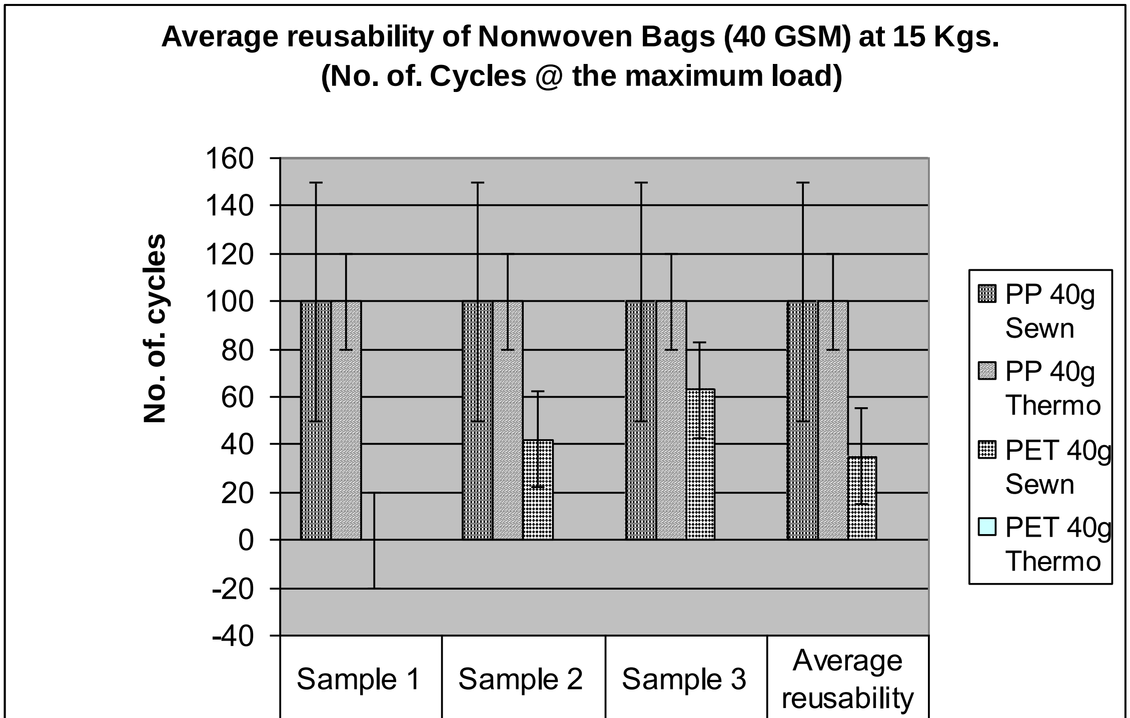
Figure 6-31 Reusability results of woven bags



	Sample 1	Sample 2	Sample 3	Average reusability
HDPE-1	100	100	26	75.3
HDPE-2	100	100	100	100
HDPE -3	100	100	100	100
LDPE-1	77	29	12	39.3
LDPE-2	45	100	100	81.7
LDPE -3	100	100	100	100

Figure 6-32 Reusability results of plastic bags

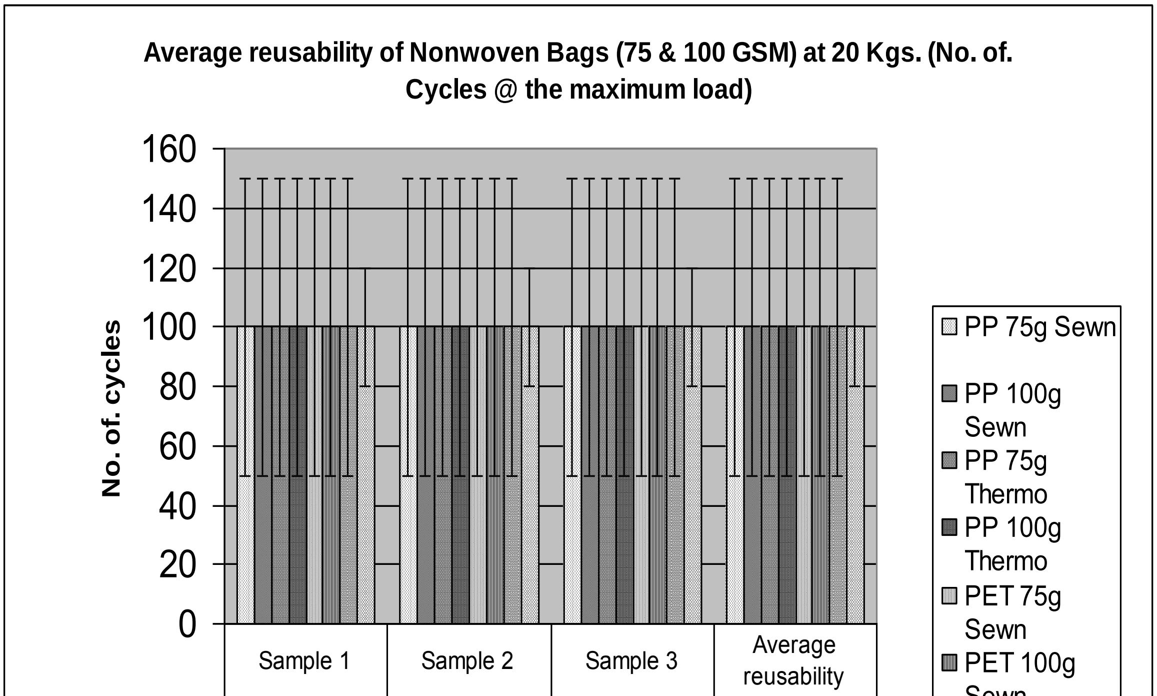
Considering nonwoven bags of different weight levels and types, a maximum holding capacity of 15 kilograms was recorded for 40 GSM bags and 20 kilograms for both 75 and 100 GSM bags. All the bags were also tested at 10, 15, 20 kgs.and the results at the maximum load are reported in Figures 6-33 and 6-34. Fig.6-33 shows the results of reusability of bags of 40 GSM. Polyester bags made by the thermo bonded technique failed abruptly as soon as the load was placed. They also failed to complete 100 cycles at 10 kilograms load for the average of 3 samples tested. Thermo bonded bags made by polypropylene of the same weight tolerated the designated maximum load due to the load bearing support extended by the nature of the fibre, i.e. polypropylene.



	Sample 1	Sample 2	Sample 3	Average reusability
PP 40g Sewn	100	100	100	100
PP 40g Thermo	100	100	100	100
PET 40g Sewn	0	42	63	35
PET 40g Thermo	0	0	0	0

Figure 6-33 Reusability results of nonwoven bags – 40 GSM

As seen from Fig.6-33, PP bags in both the thermo and sewn categories survived the maximum load of 15 kgs.for 100 cycles, while PET thermo bags fulfilled 0 and sewn bags fulfilled an average of 35 cycles at 15 kgs.of load. As indicated in Fig.6-34, all nonwoven bags of 75 and 100 GSM withstood the maximum load of 20 kgs. for 100 cycles.



	Sample 1	Sample 2	Sample 3	Average reusability
PP 75g Sewn	100	100	100	100
PP 100g Sewn	100	100	100	100
PP 75g Thermo	100	100	100	100
PP 100g Thermo	100	100	100	100
PET 75g Sewn	100	100	100	100
PET 100g Sewn	100	100	100	100
PET 75g Thermo	100	100	100	100
PET 100g Thermo	100	100	100	100

Figure 6-34 Reusability results of nonwoven bags – 75 and 100 GSM

b. Comparative Maximum Capacity

To assess the comparative maximum capacity of shopping bags, samples were tested for 500 cycles at 10 kgs. This load and number of cycles are referred from green seal standard-GS-16 (Green Seal-GS-16). Three samples were tested for each category and the average results are reported in Fig.6-35. Fig.6-35 shows that except paper bags of all weight levels and PP 40g sewn, PET 40 g thermo, LDPE-1, all other bags under discussion are capable of withstanding the prescribed load and able to complete the desired number of cycles. This is one of the very important parameters used directly for life cycle assessment simulation calculations.

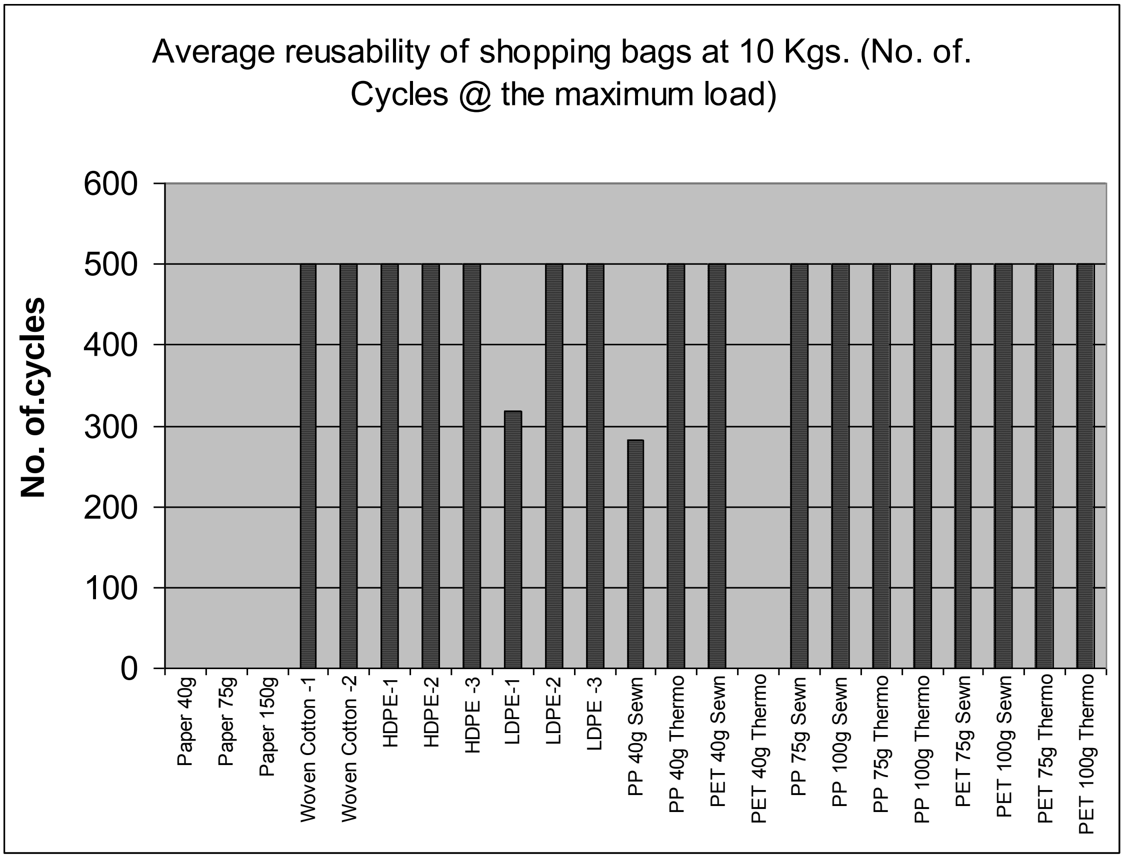


Figure 6-35 Reusability results of comparative maximum capacity

3. Impact resistance of shopping bags

a. Absolute Maximum Capacity

To assess the impact resistance function of the chosen samples, a fixed number of 5 cycles were chosen and the samples were tested at different loads between 2 and 5 kgs. For loads up to 3 kgs., a hammer of 38 mm ball diameter was utilized and for loads greater than 3 kgs., a hammer of 50 mm ball diameter was chosen.

Paper, plastic and nonwoven bags of 40 GSM withstood only 2 kgs. of load. The number of cycles they withstood at this load of 2 kgs. is reported in Fig.6-36. It is shown that all paper, plastic and PET bags (sewn and thermo) of 40 g. survived just one cycle of impact load at 2 kgs. PP bags of 40 GSM (sewn and thermo) bore an average of 2.7 cycles at 2 kgs.impact load.

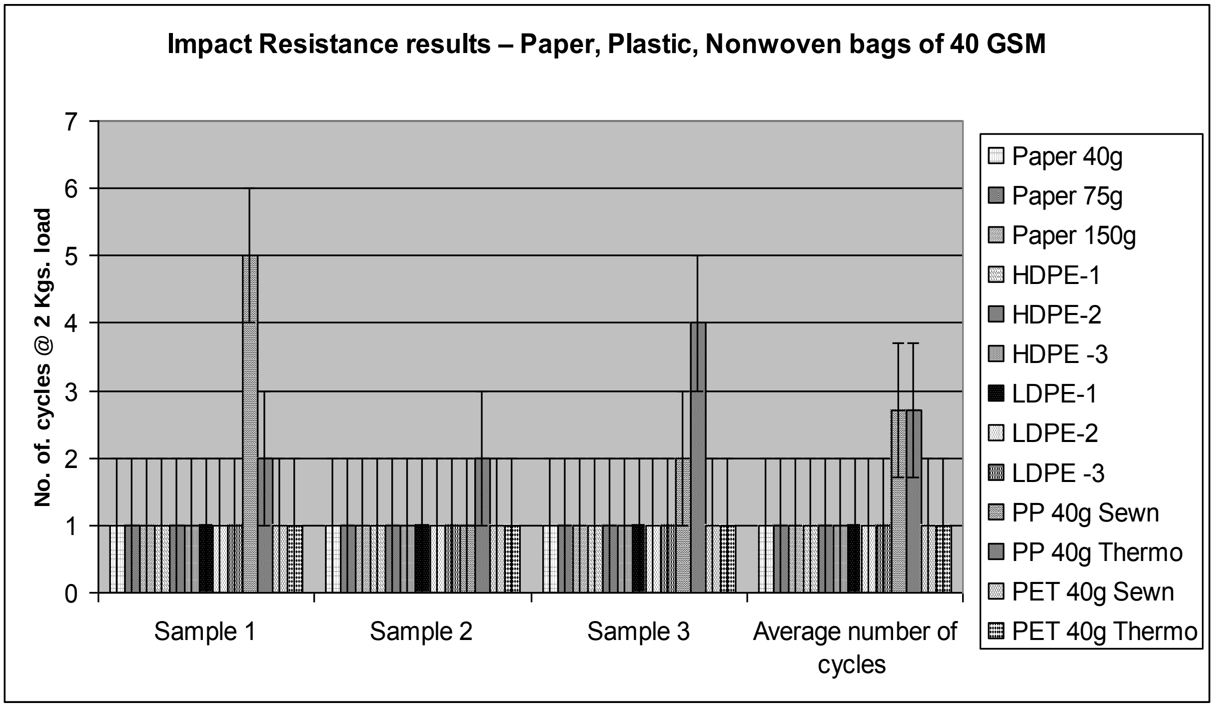
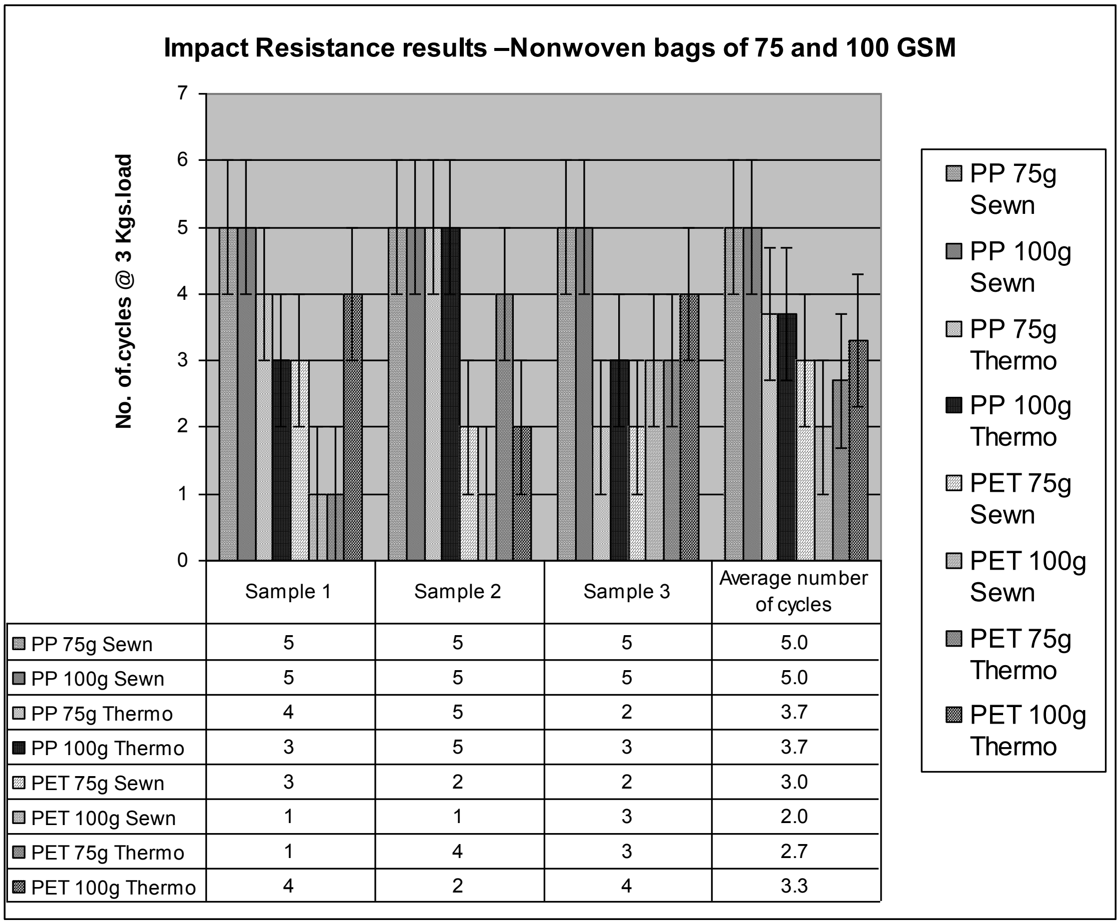


Figure 6-36 Impact Resistance results of paper, plastic, nonwoven bags of 40 GSM

Nonwoven bags of 75 and 100 GSM withstood only 3 kgs. of load and the number of cycles they withstood at the maximum load of 3 kgs. is reported in Fig.6-37. They were tested at loads between 2 kgs. and 3 kgs. As Fig.6.37 indicates, sewn PP bags of both 75 and 100 GSM, withstood a maximum of 5 cycles at 3 kgs. load and thermo PP bags of both 75 and 100 GSM endured only 3.7 cycles at 3 kgs. load.



	Sample 1	Sample 2	Sample 3	Average number of cycles
PP 75g Sewn	5	5	5	5.0
PP 100g Sewn	5	5	5	5.0
PP 75g Thermo	4	5	2	3.7
PP 100g Thermo	3	5	3	3.7
PET 75g Sewn	3	2	2	3.0
PET 100g Sewn	1	1	3	2.0
PET 75g Thermo	1	4	3	2.7
PET 100g Thermo	4	2	4	3.3

Figure 6-37 Impact Resistance results of nonwoven bags of 75 and 100 GSM

Woven bags survived the maximum load of 5 kgs. and the number of cycles they withstood at this load is reported in Fig.6-38.

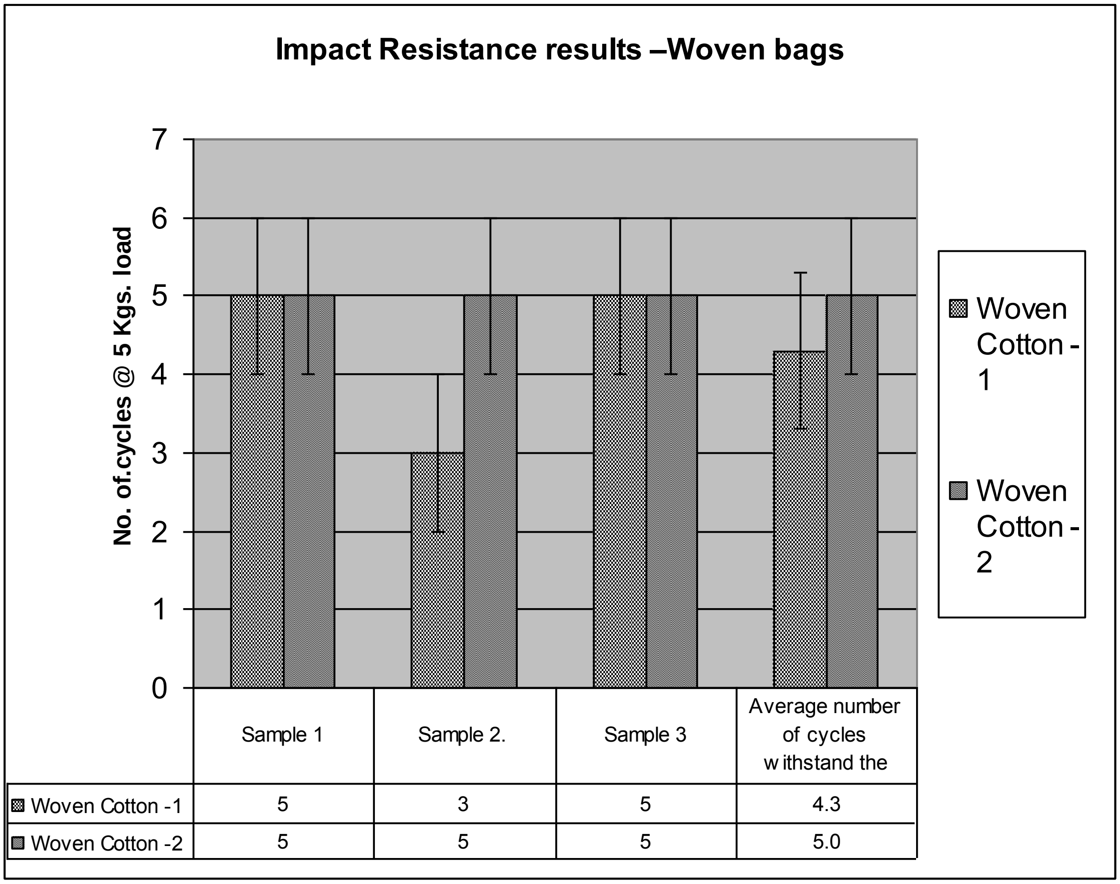


Figure 6-38 Impact Resistance results of woven bags

b. Comparative Maximum Capacity

To assess the comparative maximum capacity of shopping bags to determine their impact strength, samples were tested for the maximum number of cycles they could withstand at 5 kgs. Three samples were tested for each category and the average results are reported in Fig.6-39. From Fig.6-39, it can be seen that the nonwoven bags of 75 and 100 GSM and the woven bags are only able to fulfill the entire 5 cycles at the designated load of 3 kgs.

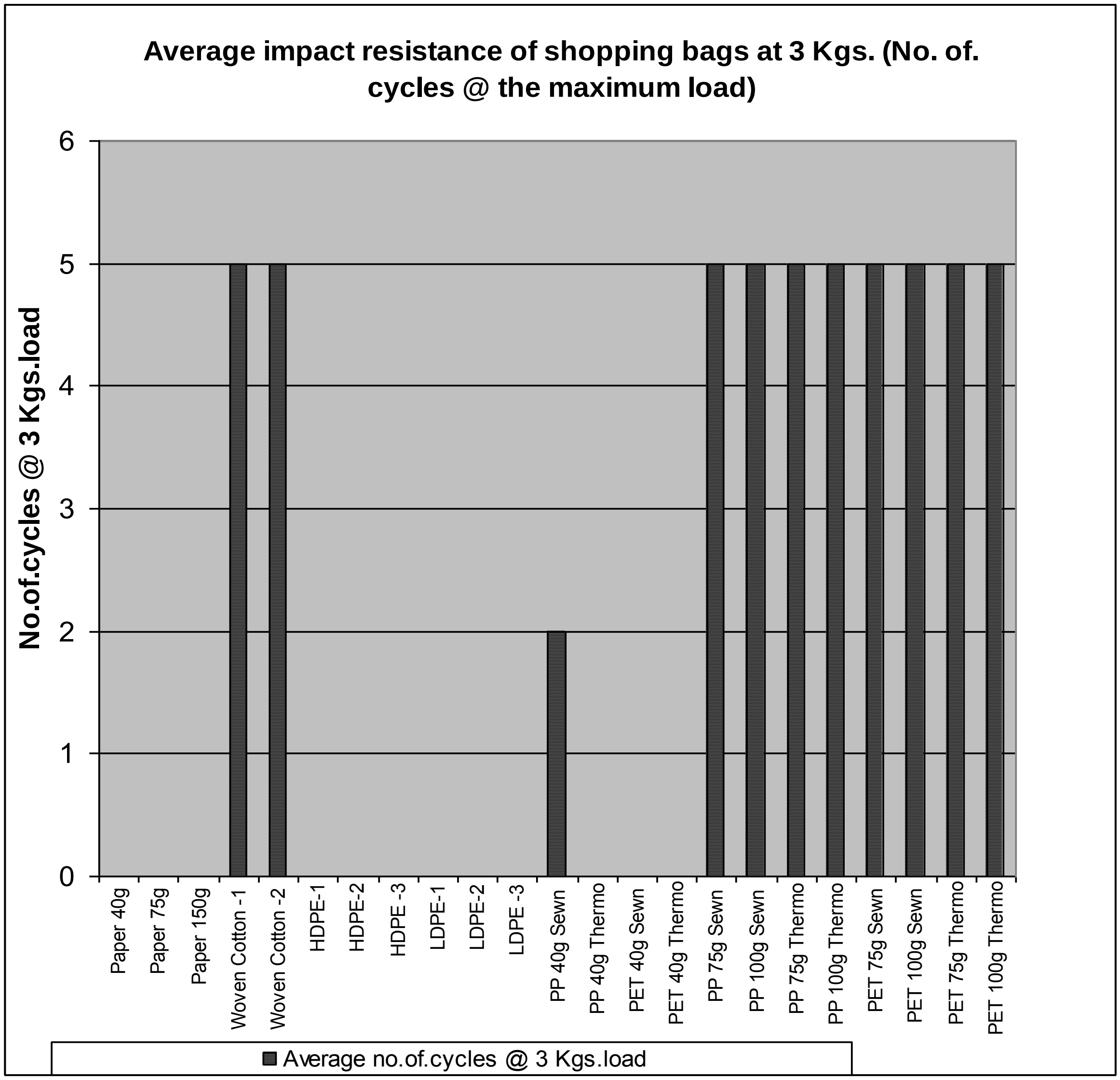


Figure 6-39 Impact Strength results of comparative maximum capacity of shopping bags

This study has reported the development of a novel instrument to assess the eco-functional properties of shopping bags used for carrying groceries. The developed instrument can test the reusability, impact resistance and weight-holding capacity functions of various shopping bags.

Quantification of eco-functional properties deserves close attention, since these properties decide the useful life time of a shopping bag. One of the values derived from this instrument, i.e. reusability is one of the main input parameters used directly in Life Cycle Assessment (LCA) calculations. The two other functional values are also very important in LCA studies, since they are the base on which the functional unit of any LCA study is decided and on which comparison of different products are made in LCA studies.

The workability of the instrument was tested by experimenting with 23 types of different categories of shopping bags and the results are reported here. Samples considered for this study were tested for reusability, impact resistance and weight-holding capacity functions. Reusability and impact resistance were reported in terms of absolute maximum capacity and comparative maximum capacity. In the single use shopping bag category, plastic bags outscored paper bags and in the reusable category woven bags top the whole list of samples chosen for this experiment.

6.5. Conclusions

This chapter discussed the study of consumption behavior relating to shopping bags by a questionnaire survey conducted among different user groups in Mainland China, Hong Kong and India. Consumption behaviour is shown to be primarily influenced by various functional and eco-functional properties. This chapter reported the testing of various functional properties of a range of shopping bags and also the development of an eco-functional tester to quantify the eco-functional properties of the different shopping bags under consideration. The details discussed in this chapter help to provide essential data to test research question 3, which was given in Chapter 3. The following chapter deals with the next phase in the life cycle of shopping bags, the disposal phase, which covers biodegradability and recyclability.

Chapter 7 Biodegradation Studies and Quantification of Recyclability Potential Index [RPI] for Fibres and Other Raw Materials

7.1. Introduction

As stated in Chapter 2, to date there is no studies available that report on evaluating the biodegradability of different types of shopping bags using the same platform. It was also pointed out that there are no models/ways to quantify the recyclability of different textile fibers and other raw materials used for shopping bags. These knowledge gaps are addressed in this chapter, which reports the biodegradability studies using the soil burial test conducted in the present research for different types of shopping bags.

This chapter also explains the concept behind the recyclability potential index [RPI] of different textile fibers and other raw materials used for shopping bags, after considering the environmental and economic gains of the recycling process. An attempt is made to quantify the recyclability potential index [RPI] of these fibres and other raw materials.

Once it is decided to dispose of the shopping bags, they have many possible destinations including reuse, recycle, landfill, incineration and so on. Reuse may not pose any environmental threats and incineration is not very common globally. Recycling and disposing to landfill are the commonest possible destinations, which are subjected to arguments pertaining to creating environmental hazards that are common in many countries including Mainland China, Hong Kong and India. The use of various shopping bags during recycling along with their biodegradation potential in landfills are very crucial matters to be studied since they eventually form the life cycle inventory for the disposal phase of shopping bags. This pertains to testing research question 4, stated in Chapter 3.

7.2. Biodegradability studies of various shopping bags

Once it is decided to dispose of products, they are expected to biodegrade, which is the best possible way of completing the life cycle of any product. As discussed earlier, shopping bags, a symbol of the throw-away society, are disposed very frequently. They have to undergo biodegradation without creating any further complications for the environment.

Whether a bag is made out of paper or plastic or cotton, it has to biodegrade at the end of its life cycle. Hence bags' potential biodegradabilities need to be evaluated using the same platform, which so far has not been reported in the literature. This study attempts to evaluate the biodegradation of various shopping bags using the same platform.

There are many standards and test methods available to test the biodegradability of various materials. Many of them demand long testing periods of around 6 months and involve difficult measurement techniques to prove the capacity of the tested material to biodegrade. Also almost all of the tests are very costly if the samples are tested by commercial agencies. One of the biodegradation measurement techniques is the soil burial test which is an effective, cheap and relatively time effective. Many studies have utilized this test to assess the ability of the samples to biodegrade such as (Chen and Cluver, 2010; Kim et al., 2005; Suh et al., 1996; Ismail et al., 2011; Azahari et al., 2009; Kumar et al., 2010; Yabannavar and Bartha, 1993; Park et al., 2003; 2004).

7.2.1. Biodegradation Experimentation Setup & Experimentation

An experiment was set up and a test chamber made out of a thick plastic container was prepared to conduct the biodegradation studies of the various shopping bags as per AATCC 30 standard (AATCC 30:2004)in lab conditions. According to AATCC 30 standard (2004), soil procured from the market with a Ph level between 5-6.5 and electrical conductivity between 0.8-1.5 was used to fill a plastic container. The soil was first dried and during the whole period of testing, the moisture content of soil was maintained at 25 +/- 5 % to comply with the conditions stipulated in the standard. The processes of drying the soil and moisture content checking are shown in Appendix 5 and the experimental setup for biodegradability assessment is shown in Fig.7-1.

A soil bed was prepared to 13 cm depth in compliance with all the conditions stated in the standard. Table 7-1 lists the sample specifications for the biodegradability test. Each sample was cut into 2.5 * 15 cm pieces and 4 samples from each category of shopping bag were prepared. Samples were buried in the soil at 3 cm depth [10 cm depth and top layer must be of 3 cm soil] and allowed to degrade for periods of 0-90 days. Figures relating to the burying process and initial check up are illustrated in Appendix 5. Moisture content was checked at regular intervals throughout the entire test period with the aid of a moisture meter. During the entire test period of 90 days, the temperature of the setup was maintained at Temperature: 28+/-2ºC with the help of a temperature control made for the test chamber (Muthu et al., 2012b).

Figure 7-1 Experimental setup of biodegradation assessment

Following the degradation period, samples were rinsed with distilled water and dried. Samples were tested for weight loss after 0, 30, 60 and 90 days and loss/gain in tensile strength, strain and extension for 0 and after 90 days. Microscopical appearance changes before and after the biodegradation were also reported. Biodegradation was evaluated in terms of both loss in weight and tensile strength.

Sample Number	Sample Name	Grams per Sq. metre [GSM]
1.	Paper 150g	158.73
2.	Woven Cotton -2	368.3
3.	PO3 (HDPE)	83.5
4.	PE3 (LDPE)	95.17
5.	PP 100g Sewn (Nonwoven Polypropylene)	104.57
6.	PET 100g Sewn(Nonwoven Polyester)	109.93

Table 7-1 Samples description for biodegradation test

7.2.2. Results and Discussion

As pointed out earlier, samples were tested after 30, 60 and 90 days for weight loss, and after 90 days for tensile strength loss and microscopical appearance changes. They were compared against the control [0 days]. In each category of shopping bags, 4 samples were tested and the results are reported as an average of 4 samples.

1. Weight loss

Weight of the samples before and after the biodegradation of 30, 60 and 90 days were measured for 4 samples in each category and the average results are reported in Table 7-2. Weight loss was calculated and reported as a percentage of control in table 7.2. Fig. 7-2 illustrates the comparison of loss in weight for different shopping bags.

Sample	No. of samples	0 days [Control]	30 days	60 days	90 days	% Weight Loss
Paper	4	0.59	0	0	0	100%
LDPE	4	0.335	0.328	0.328	0.328	2.09%
HDPE	4	0.333	0.328	0.328	0.328	1.50%
PP – NW	4	0.385	0.373	0.373	0.365	5.19%
PET-NW	4	0.353	0.353	0.353	0.348	1.42%
Cotton	4	1.345	1.2	1.09	0.818	39.18%

Table 7-2 Weight loss results of biodegraded samples

From the results, it can be understood that paper biodegraded completely. It was observed that after just a week, paper samples started disintegrating and at the end of the test period, they were completely disintegrated. Cotton samples also showed significant weight loss, which is a positive indication of biodegradation. All of the other shopping bags showed some weight loss as listed in Table 7.2, but not as much as paper and cotton.

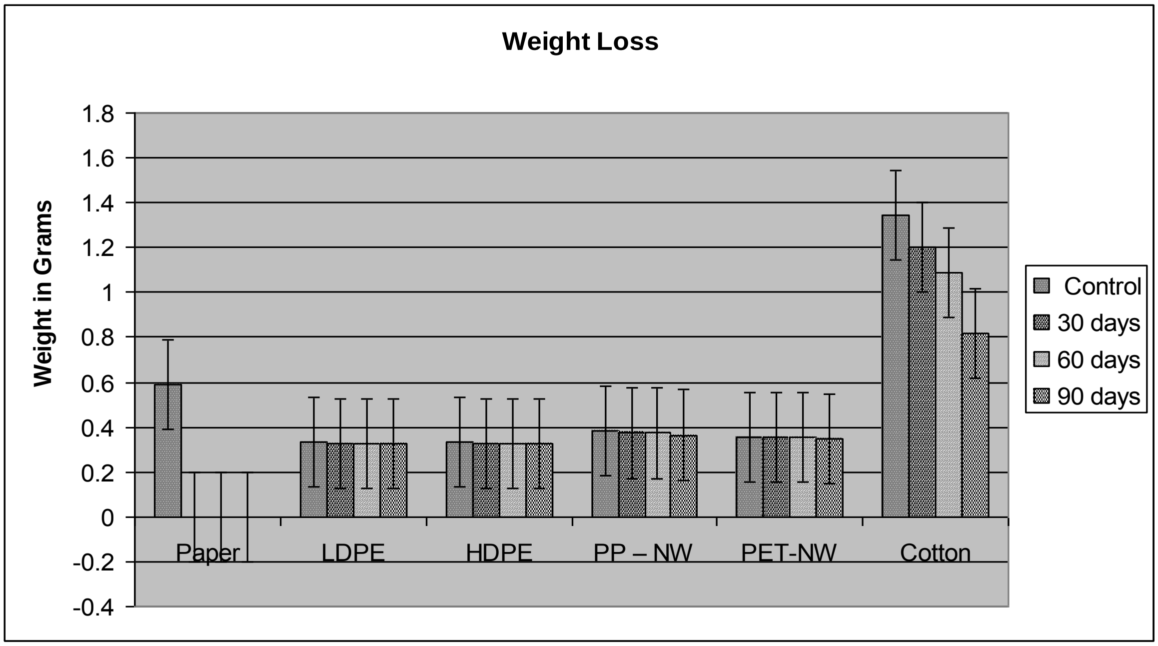


Figure 7-2 Weight loss of biodegraded samples

2. Tensile Strength

Tensile strength of the samples before and after the biodegradation of 90 days was measured as per ASTM D 5034[Grab Test] (ASTM D5034 - 09). The average results of 4 samples in each category are reported in Table 7.3. Loss in tensile strength was calculated and reported as a percentage of control in Table 7-3. The results are also illustrated in graphical format in Fig.7-3.

Samples	No. of samples	0 days [Control]	90 days	% Strength Loss
Paper	4	111.03	0	100%
LDPE	4	31.27	30.67	1.92%
HDPE	4	52.75	51.84	1.73%

PP – NW	4	70.19	63.79	9.12%
PET-NW	4	66.4	65.5	1.36%
Cotton	4	411.27	295.67	28.10%

Table 7-3 Loss in tensile strength of biodegraded samples-load in newton

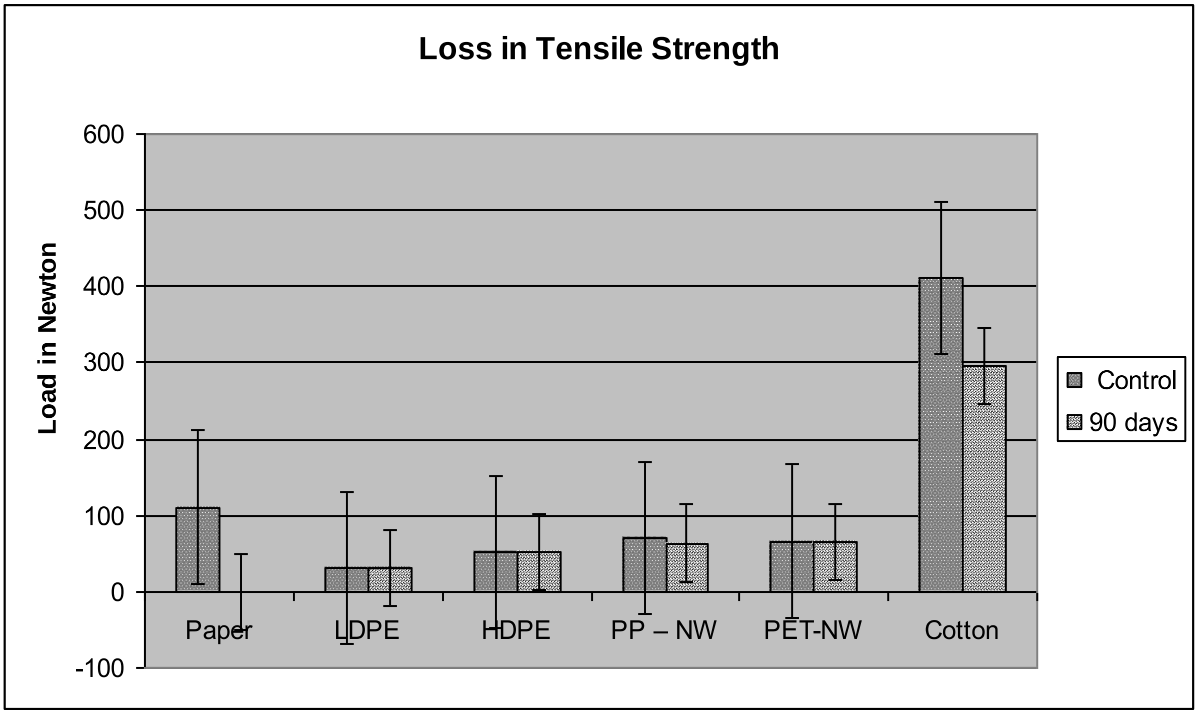


Figure 7-3 Loss in tensile strength of biodegraded samples

It can be clearly seen from the tensile strength results that they are in line with weight loss results in that the positions of the samples remain the same. Paper bags followed by cotton lost their strength values significantly. Polypropylene bags made out of nonwovens underwent around a 9% reduction in strength. Polypropylene seems to be better in terms of biodegradation in the synthetic materials category.

3. Microscopic Appearance Changes

Surface appearance changes were observed microscopically with the aid of a Leica M 165C microscope before and after biodegradation of 90 days. The results of the various shopping bags under discussion, except paper, are illustrated in Figs. 7-4 -7-9. Remarkable surface appearance changes can be seen from the cotton samples.

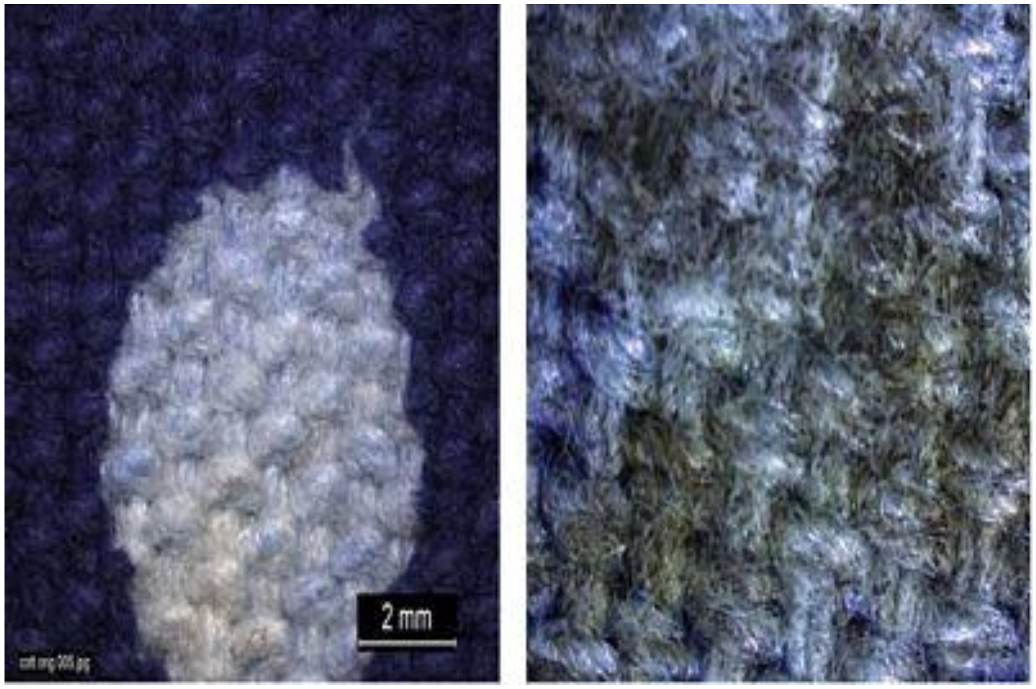


Figure 7-4 Before and after biodegradation: Cotton

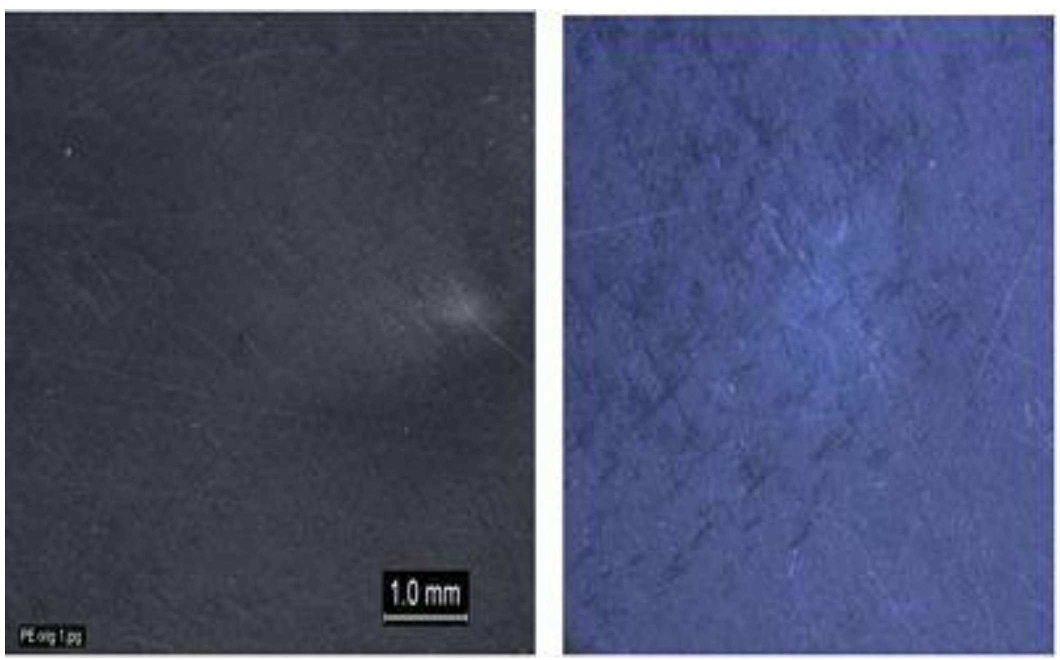


Figure 7-5 Before and after biodegradation: HDPE

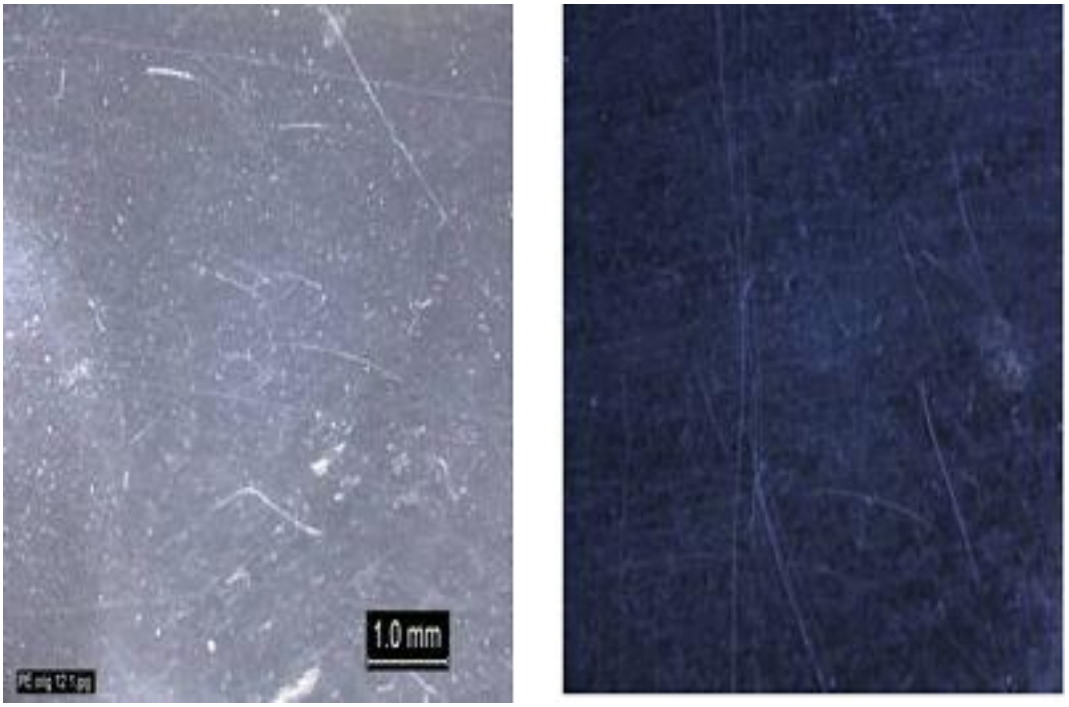


Figure 7-6 Before and after biodegradation: LDPE

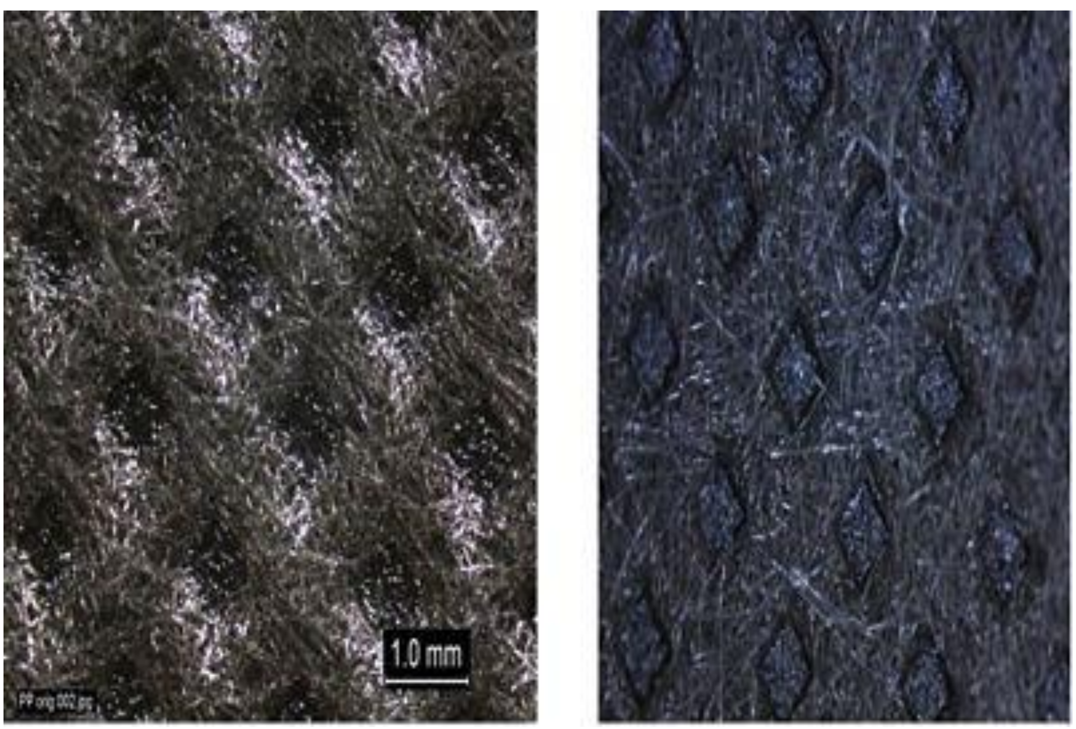


Figure 7-7 Before and after biodegradation: Nonwoven PP

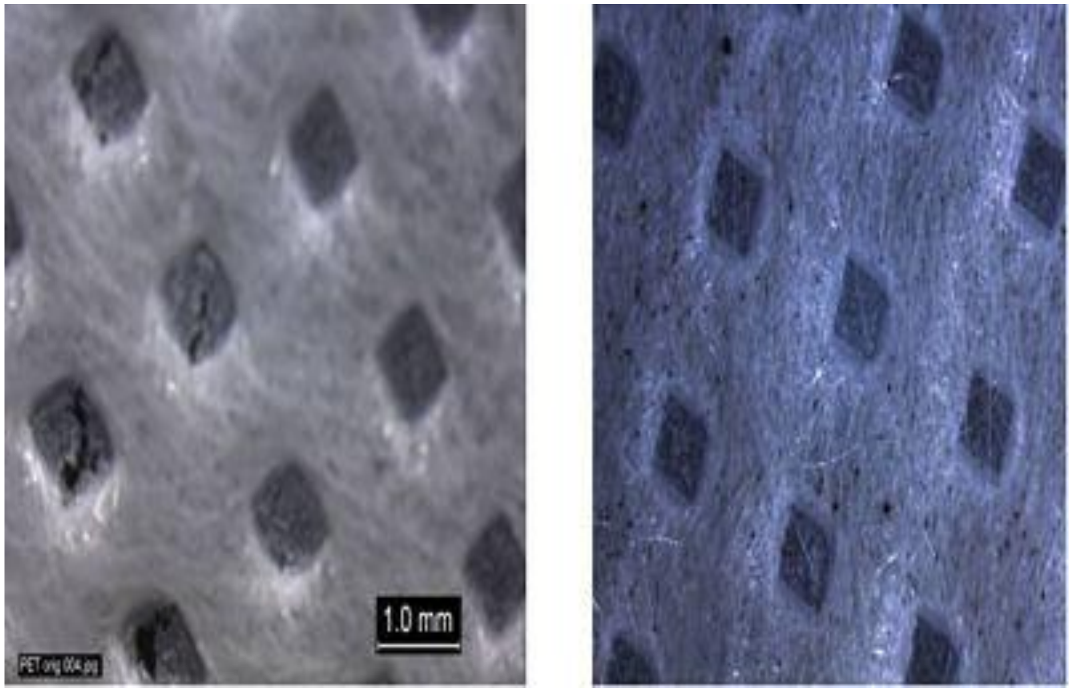


Figure 7-8 Before and after biodegradation: Nonwoven PET

From the biodegradability tests, it can be seen that the paper followed by cotton bags showed noteworthy biodegradation and polypropylene seems to be better in the synthetics category.

7.3. Quantification of Recyclability Potential Index for textile fibres and other raw materials used for shopping bags

A focus on recycling is one of the key pillars in this environmentally conscious era. With or without understanding the entire benefits/detrimental effects of the process of recycling, people are required by the alarming environmental situations/impacts to consider recycling as one of the primary scenarios at the end-of-life of any product. In recent times, the situation is forcing people to recycle everything that is produced, due to various factors such as present and future projections of scarcity of potential resources, limited landfill space, governmental policies, rewards in terms of monetary benefits given to people when they return the product for recycling. The urgency of the situation is increasing environmental awareness among the people. Textile products, including shopping bags, occupy a significant position in daily activities and need to be recycled. Many types of fibers/raw materials are being used to manufacture textile products/shopping bags for daily use and they necessarily need to be recycled at the end of their lives. The potential recyclability of different fibres and raw materials for shopping bags varies from one material to another and many factors play a major role in deciding their recyclability. This study proposes a concept for the recyclability potential index [RPI] of textile fibers and other raw materials for shopping bags, considering their environmental and economic gains from the recycling process. It also attempts to quantify the recyclability potential index [RPI] of ten common, widely used textile fibers and paper used for shopping bags.

Any product being manufactured will become technically useless after some period of its use and will reach its end-of-life stage. In the past, approximately three decades ago, those products were all disposed to landfill. But the case is entirely different now and the destination of those products is different. One of the possible destinations, which is beneficial to the environment and consequently to individuals is recycling.

Recycling involves reuse, reprocessing or reproducing a product with the multiple aims of conserving raw materials, energy, water and other chemicals, diminishing waste, preserving environmental impacts and so on. Though this is no doubt that the reuse of any material will be very beneficial in conserving the various resources listed above, it is much less applicable in the case of second hand clothing due to limited practical applicability (Bartl et al., 2005). Recycling brings ample benefits to both the environment and the economy (Economic Benefits of Recycling; Korhonenand and Dahlbo, 2007; Michaud et al., 2010; Morley et al., 2009). Unfortunately, however, it has barriers to overcome of various kinds: financial, technological, educational, legal and infrastructural. These often prevent recycling as a desirable option at the end-of-life stage (Bhalla, 2005; Gulich, 2006). Recycling of textile fibers and raw materials used for shopping bags will aid progress towards the sustainability of both products and processes (Bartl et al., 2005).

Quantifying materials in terms of their recyclability started in the recent past, almost a decade ago. The recyclability of a material should reflect many factors such as the environmental impact of the recycling process, the environmental benefits gained, the economics of the recycled material compared to its virgin counterpart, the technical quality of recycled material, the machines and technologies available to facilitate recycling and so on. Many researchers' (Sibley and Butterman, 1995; Ayres, 1997; McLaren et al., 2000; Craig, 2001; Villaba, et al., 2002; Liu et al., 2002; Krozer and Doelman, 2003; Phillis et al., 2009) contributed greatly to quantify the recyclability of various materials, but very little or almost no attempt has been made to quantify the recyclability of textile fibers. In 1995, Sibley and Butterman (1995) ranked 22 metals by the rate and efficiency of recycling and also by the availability of the recycled metals. In 1997, Ayres included the environmental and economic aspects in his concept of analyzing the recyclability of metals (Ayres, 1997). Later on, an environmental assessment of recycling systems was made by McLaren et al. in 2000, with the aid of their developed methodological framework (McLaren et al., 2000). Recyclability was defined by Craig in 2001 using the chemical and thermo dynamical properties of materials. Crain proposed three indicators: chunk size, concentration, and bonding (Craig, 2001). In 2002, another important contribution was made by Villaba et al. made people to look at the recyclability of materials in terms of the monetary benefits gained by recycled materials compared to their virgin counterparts (Villalba, et al., 2002). A recyclability assessment based on an artificial neural network was proposed by Liu et al. (2002) in the same year and various policy dimensions for recycling were assessed by Krozer and Doelman in 2003 (Krozer and Doelman in 2003). Recently, Philips, et al., (2009) proposed a fuzzy assessment of material recyclability, by taking account of various factors embedded in human and physical inputs.

However, the previously conducted studies have not focused or put an emphasis on textile fibers and paper, which are addressed in the present research. This mainly focuses on developing a conceptual model to quantify the recyclability of textile fibers and paper used for shopping bags in economic and environmental terms. Environmental benefits include conservation of essential resources such as energy, water for the production of virgin material, environmental impact of production of virgin material include ecological and carbon footprint, human health impacts, environmental impact of land filling the material instead of recycling and finally the benefit of recycled materials in terms of energy conservation compared to virgin materials. The monetary benefits of recycled materials proposed by Villaba et al., (2002) are considered for calculating the economic benefits of recycled materials.

In this study, the proposed concept of a Recyclability Potential Index [RPI] is tested for ten important textile fibres such as nylon 6 and 66, viscose, acrylic, polyester, wool, cotton, polypropylene, polyethylene's [LDPE and HDPE] and paper used for manufacturing shopping bags.

7.3.1. The concept of Recyclability Potential Index [RPI]

A Recyclability Potential Index [RPI] cannot be decided by considering a single factor of a textile fibre or of any material. It is a composite factor, taking into account numerous factors from various perspectives. Though there are many possible factors to be looked at, at this moment, only environmental and economic sides are taken into consideration to derive RPI (Muthu et al., 2012c).

$RPI = \sum EGI_1 + EGI_2,$

where EGI_1 – Environmental Gain Index

EGI_2 – Economic Gain Index.

$EG_1 = \sum X_1 + X_2 + X_3 + X_4,$

where X_1 = Saving potential resources

X_2 = Environmental impact caused by producing virgin fibres/materials

X_3 = Environmental impact due to land filling

X_4 = Environmental benefits gained out of recycling versus incineration

$EG_2 = x_1 / x_2,$

Where x_1= Price of recycled fibre/material; x_2 = Price of virgin fibre/material.

7.3.2. Derivation of Recyclability Potential Index [RPI] of textile fibres and other raw materials used for shopping bags

1. Environmental gain index: data collection

1.1. Saving potential resources

Enormous resources are spent to produce 1 kg of a textile fibre/ other raw materials used for shopping bags. Two major potential resources, which may be in huge demand in near future, are being spent in producing any textile fibre. They are energy and water and Table 7-4 lists the energy and water needs for the production of 1 kg of virgin fibre.

Fibre	Energy use in MJ per kg of fibre/ material	Water requirement per kg of fibre/ material
Nylon 6	120.5 (Boustead, 2005)	185 kgs. (Boustead, 2005)
Nylon 66	138.7 (Boustead, 2005)	663 kgs. (Boustead, 2005)
Viscose	100.0 (Barber and Pellow 2006)	640 Litres (Laursen et al., 1997)
Acrylic	175.0 (Barber and Pellow 2006)	210 Litres (Laursen et al., 1997)
Polyester	125.0 (Barber and Pellow 2006)	62 kgs. (Boustead, 2005)
Cotton	60.0 (Kaillala and Nousiainen, 1999)	22000 kgs. (Kaillala and Nousiainen, 1999)
Wool	63.0 (Barber and Pellow 2006)	125 L; 5-40 Litres [Scouring] (Laursen et al., 1997)
PP	115.0 (Barber and Pellow 2006)	43 kgs. (Boustead, 2005)
LDPE	78.1 (Boustead, 2005)	47 kgs. (Boustead, 2005)
HDPE	76.7 (Boustead, 2005)	32 kgs. (Boustead, 2005)
Paper	21.6 (Wake Up To Waste Kids)	300 Litres (Wake Up To Waste Kids)

Table 7-4 Energy and water needs to produce 1 kg of fibre/raw material for shopping bag (results rounded-off)

1.2. Environmental impact caused by producing virgin fibers/other raw materials

The other important aspect to be looked at while discussing the environmental gains is the environmental impact caused by producing virgin fibres/materials. Three major environmental impacts such as ecological, carbon footprints and ecological damage in terms of human health are considered here. To arrive at these figures, the impacts were modeled with the aid of SIMAPRO version 7.2. Environmental impacts in the above categories were modeled for producing 1 kg of virgin fibre with the aid of suitable datasets available in SIMAPRO version 7.2. Ecological footprint was modeled by Ecological Footprint V1.00, carbon footprint was modeled by IPCC 2007 GWP 100a method and ecological damage was quantified by the Ecoindicator'99 method, where only human health impacts were considered. Relevant information pertaining to these methods can be obtained from (Life Cycle Impact Assessment Methods). The results for all ten fibres can be in Table 7-5.

Fibre/raw material	Total Ecological Footprint in Pt	IPCC GWP 100a in kg CO2 eq	Ecological Damage - Human Health in mPt
Nylon 6	16.2	9.2	109.0
Nylon 66	20.2	8.0	91.5
Viscose	36.4	1.8	126.0
Acrylic	7.8	3.2	36.8
Polyester	7.9	2.8	38.6
Cotton	0.001	0.4	82.4
Wool	604.0	86.0	2480.0
PP	5.3	2.0	22.0
LDPE	6.0	2.1	25.6
HDPE	5.1	1.9	22.5
Paper	0	0.375	12.5

Table 7-5 Environmental impacts caused during virgin fibre/raw material production

1.3. Environmental impact due to land filling

The third factor to be considered is the importance of recycling, in other words the detrimental effects of land filling. If the material is not going to be recycled [assuming that it is not going to be reused but rather disposed of], its next destination could be landfill, which is a nightmare to environmentalists and even to the public due to limited space in the first place and also because of its negative effects on the environment.

To model this scenario, the environmental impact of keeping 1 kg of any textile fibre/paper under consideration was modeled with the aid of SIMAPRO version 7.2 LCA software. As a last step, environmental effects were measured by means of ecological, carbon footprints and ecological damage in terms of human health. The results of this scenario are given in Table 7-6.

Fibre/raw material	Total Ecological Footprint in mPt	IPCC GWP 100a in g CO2 eq	Human Health in mPt
Nylon 6	89.7	89.7	108.0
Nylon 66	89.7	89.7	108.0
Viscose	77.5	700.0	20.0
Acrylic	77.5	700.0	20.0
Polyester	77.5	700.0	20.0
Cotton	77.5	700.0	20.0
Wool	77.5	700.0	20.0
PP	92.8	96.8	42.5
LDPE	102.0	113.0	50.3
HDPE	102.0	113.0	50.3
Paper	70.1	1.35	10.2

Table 7-6 Environmental impacts of fibre/raw material due to land filling

1.4. Environmental benefits gained out of recycling versus incineration

The final factor to be considered is the environmental benefit of recycling versus incineration. The results of this consideration for all of the fibres and raw materials used for shopping bags considered here are listed in Table 7-7.

Fibre/raw material	Energy conserved, in kilowatt hours per ton [1]	Energy generated, in kilowatt hours per ton [2]
Nylon 6 (Morris and Canzoneri,1992)	4889	611

Nylon 66 (Morris and Canzoneri,1992)	4889	611
Viscose (Morris and Canzoneri,1992)	4889*	611*
Acrylic (Morris and Canzoneri,1992)	4889	611
Polyester (Morris and Canzoneri,1992)	7203	1761
Cotton (Morris and Canzoneri,1992)	3531	611
Wool (White et al., 1995)	16389	Data Not Available
PP (Morris and Canzoneri,1992)	5776	1407
LDPE (Morris and Canzoneri,1992)	6330	1222
HDPE (Morris and Canzoneri,1992)	6232	1761
Paper (Morris and Canzoneri,1992)	1878	706

Table 7-7 Environmental benefits of Recycling Vs Incineration

[1] Substituting secondary materials for virgin raw materials.
[2] Incinerating municipal solid waste.
*- Data taken from the value of synthetics.

2. Economic Gain Index: Data Collection

Economy is one of the major deciding factors which can promote or demote recycling. In this context, economy refers to the market potential for recycled fibres/materials in terms of the appreciation in terms of money value. This index can be derived from the ratio of the price of recycled material to the price of virgin material of same kind and unit in the market. This ratio determines many factors (Villaba et al., 2002).

Table 7-8 below presents the values of both recycled and virgin materials obtained from the market.

Fibre / raw material	Virgin Fibre Prices in Yuan/Ton.	Description and Source	Recycled Fibre Prices in Yuan/Ton	Description and Source	EGI_2
Nylon 6	24300	Conventional (Ccfei.net, 2010)	18800	Grade 1. Recycled chips from waste yarns. Original colour with luster. (Chinanylon.com)	0.77

Nylon 66	63500	15D/7F DTY (Texnet.com, 2010 a)	20000	Grade 1. Recycled chips from waste yarns. Original colour with luster. (Chinanylon.com)	0.31
Viscose	19355	1.5D VSF (Ccfei.net, 2010)	5000	Waste Viscose Fibre (Zz91.com)	0.26
Acrylic	22800	1.5D (Ccfei.net, 2010)	11300	Original colour PMMA broken materials. Can be directly used or be granulated. (Worldscrap.com (a))	0.50
Polyester	10131	1.4D PSF(Ccfei.net, 2010)	8339	Re-PSF-High quality white 1.5 D. (Ccfei.net, 2010)	0.82
Cotton	16877	Cotton 328(Ccfei.net, 2010)	4000	Length of Fiber: 1.5-2.5cm. (Diytrade.com)	0.24
Wool	53262	AWEX EMI (Woolinfo.net)	9000	Waste Wool in different quality level, good softness. Can be used in many methods, mainly used for spinning and man-made wool flat. (Yuancailiao.net)	0.17
PP	11600	1.5D*38mm (Texnet.com, 2010 b)	7500	Transparent, pure and clean. Can be directly used or be granulated. (Worldscrap.com (b))	0.65
LDPE	10550	(Alibaba.com (a))	6700	Transparent, transition waste, pure. Can be re-used or be granulated. (Worldscrap.com (c))	0.64
HDPE	9100	(Alibaba.com (b))	6600	Transparent, transition waste, pure. Can be re-used or be granulated (Worldscrap.com (d))	0.73
Paper	4700*	(Paper.com.cn)	1500	(whtpaper.com)	0.32

Table 7-8 Prices of virgin and recycled materials and EGI_2

7.3.3. Quantification of environmental, economical gain indices and RPI

At present, many values are available with different units under different headings. To unify them and to obtain separate indices of EGI_1 and EGI_2 and consequently obtain RPI, a scaling template has been developed. This scaling template consists of five scales ranging from 1 to 5. All of the available values at this point are classified into this five point scaling based on the available values.

The scaling template developed for different scenarios is given in Table 7-9 and the corresponding values in each category can be seen in Table 7-10. Quantified RPI values for each fibre/raw material used for shopping bag can also be seen in Table 7-10.

Energy [MJ]		Water [kgs.]	
<50	1	<100	1
51- 100	2	101-200	2
101-150	3	201-300	3
151-200	4	301-400	4
>201	5	>401	5
E.I. of Virgin – EFP		E.I. of Virgin – CFP	
<5	1	<2	1
5.1-10	2	2.1-4	2
10.1-20	3	4.1-6	3
20.1-30	4	6.1-8	4
>30.1	5	>8.1	5
E.I. of Virgin – HHI		E.I. of Landfill-EFP	
<20	1	<50	1
21- 40	2	51- 100	2
41-60	3	101-150	3
61-80	4	151-200	4
>81	5	>201	5
E.I. of Landfill– CFP		E.I. of Landfill– HHI	
<100	1	<20	1
101- 300	2	21- 40	2
301- 500	3	41-60	3
501 -700		61-80	4
4 >701		>81	5
5			
Energy Conserved		EGI_2	
>15001	1	>0.81	1
15000-11001	2	0.8-0.61	2

11000-7001	3	0.6-0.41	3
7000-3001	4	0.4-0.21	4
<3000	5	<0.20	5

Table 7-9 Scaling Template

7.3.4. Results and Discussions

Table 7-10 presents the calculated RPI values of the ten chosen fibres and paper for quantification of RPI. From the scaling template, the criteria for RPI interpretation can be understood as the lower the RPI value, the better the recyclability. Table 7-11 gives the RPI values and the ranking in terms of recyclability of the chosen ten fibres and paper.

Fibre/raw material	EGI_1	EGI_2	RPI
Nylon 6	30	2	32
Nylon 66	33	4	37
Viscose	29	4	33
Acrylic	24	3	27
Polyester	20	1	21
Cotton	25	4	29
Wool	27	5	32
PP	19	2	21
LDPE	21	2	23
HDPE	20	2	22
Paper	20	4	24

Table 7-10 EGI_1, EGI_2, and RPI of fibres and paper

Fibre/raw material	RPI	Ranking in terms of Recyclability
Nylon 6	32	7
Nylon 66	37	9
Viscose	33	8
Acrylic	27	5
Polyester	21	1
Cotton	29	6
Wool	32	7
PP	21	1
LDPE	23	3

HDPE	22	2
Paper	24	4

Table 7-11 RPI and Ranking in terms of Recyclability

From Table 7-11, one can understand that polyester and polypropylene outperform all the fibres under consideration. They surpassed all of the chosen fibres in both the environmental and economic aspects. Polypropylene scored ahead of polyester in environmental considerations and polyester outscored polypropylene in the economic aspect; thereby both become jointly occupy best position in terms of RPI.

In this system, HDPE and LDPE are ranked in second and third positions respectively. They occupy the same position as PP as far as the economic gain index is concerned. However, their slightly lower environmental gain indices have brought HDPE and LDPE to their current positions. Paper and Acrylic gained 4th and 5th positions respectively. Though paper was better and in environmental terms was equal to HDPE, due to its lower economic gain index, it was pushed into 4th position.

Cotton assumed the next lowest economic gain index and its environmental impacts are also comparatively higher than the fibres discussed, hence it is ranked 6th in this system. For similar reasons, wool was ranked 7th among the fibres under consideration. Also wool assumed the lowest economic gain index value. Nylon 6 assumed joint 7th position with wool.

Although viscose's economic gain index is slightly better than wool and equivalent to cotton, due to its greater environmental impacts, it was ranked 8th, next to cotton and wool. Nylon 66 was ranked last and second last in this system of ranking textile fibres and paper in terms of their recyclability.

The developed model is very flexible and can be applied to an entirely different set of data considering various other factors, apart from the ones considered in this present work. Also one can use this model to study the recyclability of any fibre and also any other material with a completely different scaling template as well, since the scaling template used here in this model is a subjective one. This is of course, a limitation of the model as well as a benefit (Muthu et al., 2012c).

Also many other factors such as technological challenges on sorting and recycling facilities, different recycling policies/pressures exerted on different textile materials, availability of different fibres for recycling, rate and efficiency of recycling, quality of recycled materials compared to virgin materials etc also need to be taken into consideration. At present, these factors were not included in this proposed model due to lack of data.

This model takes into consideration of various factors for calculating environmental gain index, namely saving potential resources (water and energy), environmental impact caused by producing virgin fibres, environmental impact due to land filling and environmental benefits gained out of recycling versus incineration. The model also considers another important index, economic gain index, which focuses primarily on the monetary value of recycled material/fibre vis-à-vis virgin material. This monetary value indirectly portrays various factors taken into consideration such as energy needs for the process of recycling, technology available for recycling, quality of recycled material and so on. These factors are not considered for the calculation of environmental gain at present, due to lack of data, as admitted earlier. However, this model can further be improved upon considering various factors separately for economic gain also in future, based on the available data. In doing so, economic gain also results from various factors, as environmental gain, thereby the value RPI is resultant of equal weights from different factors arising from environmental and economic gains. Additionally, environmental gain considerations will also be improved upon in the light of various factors discussed above; thereby the scaling system can be unified for both environmental and economic gains equally.

Among textile materials, union fabrics and blended fabrics are very common. Hence the issue of separating the blended fibres and their compatibility with their constituents needs to be assessed and it must also be addressed separately. The potential use of recycled fibres and their potential for spinning in comparison with virgin fibres also needs to be addressed.

An entire dataset on recycling of textile materials and other materials used for shopping bags needs to be developed based on the above factors. The lack of such as a dataset is a major handicap for textile researchers in terms of life cycle considering recycling possibilities of textile materials.

This proposed model provides a simple and effective means to quantify the potential recyclabilities of different textile fibres considering their environmental and economic impacts. As discussed earlier, the scaling template developed is quite arbitrary but can be further rationalized through an open discussion among various textile sectors and institutions.

This study has made an attempt to quantify the Recyclability Potential Index [RPI] of different textile fibres and paper, considering their environmental and economic impacts in the process of recycling. The developed model has been used to rank ten important textile fibres and paper in terms of their recyclability.

This research made a special emphasis on textile materials and paper, considered different factors to quantify their recyclability in terms of both environmental impacts and economical benefits. Factors such as saving potential resources, limiting environmental impact caused by producing virgin fibres, reducing by recycling versus incineration were considered in terms of studying their environmental impacts. The ratio of price of recycled fibre to virgin fibre was also considered in terms of the economic benefits gained from recycling.

According to the proposed model for quantifying the RPI, polyester is ranked first followed by polypropylene and HDPE and Nylon 66 is ranked last in terms of recyclability. However, the results are based on the scales given to each material according to the scaling template developed and the scaling template was developed using secondary data for the various factors and also the quantification of certain impact results provided by the LCA software, which itself is based on certain hypotheses and assumptions.

7.4. Conclusions

This chapter discussed the biodegradation studies of various shopping bags, where paper bags followed by cotton bags showed remarkable biodegradation and polypropylene bags out scored all other synthetic counterparts. Development of a unique model to quantify the recyclability potential index of various textile fibres and paper used for shopping bags was also discussed in this chapter. According to the developed model, Polypropylene and polyester outperformed their counterparts under consideration as far as recyclability is concerned. Biodegradability and recyclability potentials of various fibres/shopping bags discussed in this chapter constitute the LCI of the disposal phase of various textile materials/shopping bags, which will in turn be used to test the research question 4 framed in Chapter 3.

Chapter 8 Integrated Eco-Functional Assessments

8.1. Introduction

This chapter fulfils the final knowledge gap/objective identified in Chapter 2 and it discusses the key issues of the whole study, i.e. eco-functional assessments of shopping bags. Though the whole concept can be applied to any textile product, the case of shopping bags is described in this research work.

This chapter reports the eco-functional assessments carried out in two areas. The first area is assessment of any textile product/shopping bag in terms of eco-functionality aspect and the method of deriving an eco-functional index/score of any textile product / shopping bags. The second area is the testing of four research questions formed in Chapter 3 by conducting an eco-functional assessment combined with life cycle assessment (LCA) which primarily revolves around the assessment of carbon footprint, eco-damage and ecological footprint of different life cycle phases of various shopping bags with the aid of SIMAPRO version 7.3 of LCA software (Version 7.2 was updated to SIMAPRO 7.3 by PRE Consultants, Netherlands and available from March 15, 2011 onwards).

8.2. Eco-functional assessment

The concept and outline of the theoretical framework of eco-functional assessment were discussed in section 3.1 of Chapter 3. This section deals with the values of inputs, the way they are connected with outputs and the derivation of the eco-functional index/score for any textile product/shopping bag (Li et al., b).

8.2.1. Values of inputs -Modelling inputs

1. Fibre/ raw material

The first input is fibre/raw material used for the manufacture of the end product, i.e. shopping bags in this framework. As discussed in Chapter 4, two numerical values- EI (Environmental Impact Index) and ESI (Ecological Sustainability Index) of ten widely used textile fibres (Conventional and Organic Cottons, Flax, Wool, Nylon 6 and 66, Polyester, Polypropylene, Acrylic and Viscose) and other raw materials used to manufacture frequently used shopping bags (Low Density Polyethylene (LDPE), High Density Polyethylene (HDPE) and paper) were quantified by a separate multi-factorial model. The numerical values of EI (Environmental impact Index), ESI (Ecological Sustainability Index) and ESIR (Ecological Sustainability Index Ranking) for the different raw materials listed above are considered in this model are given below in Table 8-1. Also based on the values of EI, ESI and ESIR of ten fibres, the same values of their common and possible blends (80%Cotton / 20%Polyester, 67%Cotton / 33%Polyester and 50%Cotton / 50%Polyester) were also developed and used in this model.

Fibre	EI	ESI	ESIR
Cotton	16	57	3
Organic Cotton	11	71	1
Wool	21	44	5
Flax	12	68	2
Nylon6	30	21	6
Nylon 66	31	19	7
Polyester	30	21	6
Polypropylene (PP)	34	11	9

Acrylic	38	0	10
Viscose	19	49	4
Paper	12	68	2
LDPE	31.5	17	8
HDPE	31.5	17	8
80Cotton 20Poly	18.8	50	4
67Cotton 33Poly	20.62	45	5
50Cotton 50Poly	23	39	5

Table 8-1 EI, ESI and ESIR of fibres/raw materials

2. Process of manufacture

The second input is the manufacturing process. Life cycle inventory of various shopping bags were collected and various values such as carbon footprint and ecological resources footprint were calculated by impact values pertaining to the average Chinese consumer for LCA calculations.

3. Functional properties

The third input is the functional properties of shopping bags, which were derived from the results of the tests, as shown in Table 3-2 (as discussed in Chapter 3).

4. Ecological properties

The fourth input is the ecological properties of shopping bags, which were derived from the results of the tests given in Table 3-3 (as discussed in Chapter 3).

For the determination/quantification of recyclability, a separate model was developed and was described in detail in Chapter 7. The Recyclability Potential Index (RPI) of different types of textile fibres and raw materials considered for the production of shopping bags was quantified by the developed model. The resultant RPI and ranking in terms of RPI of various raw materials are tabulated in Table 8-2.

Fibre	RPI	Ranking in terms of recyclability (RPI rank)
Nylon 6	33	9
Nylon 66	38	10
Viscose	32	8
Acrylic	26	5
Polyester	20	1
Cotton	28	6
Wool	31	7
PP	20	1
LDPE	23	3
HDPE	22	2
Paper	24	4
50% Cotton, 50% PET	29	6
67% Cotton, 33% PET	25	5
80% Cotton, 20% PET	26	5

Table 8-2 RPI and RPI ranking of different raw materials

8.2.2. Input & output variables linking

The following section describes the linking of various inputs and outputs selected for this model, which is one of the key issues in this research work.

1. Fibre/ raw Material

As shown in Table 8-1, there are 10 rankings given to various textile fibres/ other raw materials used for the production of shopping bags. Table 8-3 shows the rules framed for the first input, i.e. fibre/ other raw materials. Following the established rules, different raw materials are classified in terms of the ESIR and the outputs are environmental and human impacts (R_{EI} and R_{HI}).

Rule No.	IF R_{ESIR} is		R_{EI} and R_{HI} is
1	1	THEN	Close to None
2	2		Very Less
3	3		Less
4	4		Moderately less
5	5		Moderate
6	6		Moderately high
7	7		High
8	8		Very High
9	9		Extreme
10.	10		Extremely High

Table 8-3 Rules for input -1

2. Process of manufacture

For input no.2, the relevant outputs to be connected are:

1. Human Impact - Human Toxicity Potential
2. Environmental Impact (From LCA)

- Carbon footprint
- Ecological footprint
- Environmental burden - Emissions
- Environmental burden - Resources

The two outputs are connected by the equations given below (Guinee et al., 2002):

1. Human impact from life cycle analysis output – Calculation

Human toxicity values were calculated with the aid of Eq. 5.5.

2. Environmental impact from life cycle analysis outputs– Calculations

Climate change (carbon footprint)

Carbon footprint values were calculated from Eq. 5.3.

Ecological resources footprint (depletion of abiotic resources in China)

Abiotic Depletion values were calculated with the aid of Eq. 5.2.

Environmental burden- emissions

Environmental burden- Emissions values were calculated using Eq. 5.1.

As discussed in Chapter 5, life cycle inventory details of shopping bags were taken from secondary data sources (Nolan ITU et al., 2002; Excelplas Australia et al., 2004) and life cycle impact assessment calculations were performed manually with the equations listed above for the parameters of human toxicity and environmental impact (carbon footprint, ecological resources footprint for the Chinese values and environmental burden which is expressed in terms of environmental load units for emissions). Detailed equations and values were discussed in Chapter 5. Table 8-4 lists the exact values for each shopping bag and Table 8-5 shows the range of values for various shopping bags for the established parameters and the pass/fail criteria.

Impact Category	Plastic bag (HDPE)	Paper Bag (Kraft)	PP fibre Nonwoven bag	Woven Cotton Bag	Boutique plastic (LDPE)
Carbon footprint	1.19E-01	4.03E-01	3.50E+00	5.04E+00	4.46E-01

Human Toxicity	6.86E-02	2.45E-01	1.96E+00	3.08E+00	2.59E-01
Environmental Burden-ELU-Emissions	7.69E-03	2.61E-02	2.26E-01	3.26E-01	7.69E-03
Ecological Resources footprint	1.17E-06	4.16E-06	3.24E-05	5.21E-05	1.17E-06

Table 8-4 LCA values for various shopping bags

Parameter	Range	Pass/Fail Criteria
Carbon footprint	118-9650 g/CO_2	<50% Pass >50% Fail (R_{EI})
Ecological resources footprint	ADP Chinese- 0.00117 -0.1 g antimony eq./kg	<50% Pass >50% Fail (R_{EI})
Environmental Load Units	Emissions-0.0076 -0.33 per kg	<50% Pass >50% Fail (R_{EI})
Human Toxicity	68.6- 5891.1 g 1,4-DCB eq./kg	<50% Pass >50% Fail (R_{HI})

Table 8-5 Range of values of LCA parameters and pass/fail criteria for input-2

3. Functional properties

Table 8-6 shows how input no.3 links to the relevant outputs, i.e. quality, functionality and human safety. Table 8-7 reveals the range of values of different tests taken from Chapter 6 and the pass/fail criteria for various tests.

Test	Criteria	Output
Material Composition	PASS (Meets the declaration)	Quality (R_Q)
Tensile strength and elongation of material	PASS (Meets the requirement)	Functionality (R_F)
Tear strength	PASS (Meets the requirement)	Functionality (R_F)
Thickness	PASS (Meets the requirement)	Quality (R_Q)
Weight	PASS (Meets the requirement)	Quality (R_Q)
Bursting strength	PASS (Meets the requirement)	Functionality (R_F)
Colour fastness to friction/rubbing	PASS (Meets the requirement)	Quality (R_Q)
Colour fastness to washing	PASS (Meets the requirement)	Quality (R_Q)
Colour fastness to water	PASS (Meets the requirement)	Quality (R_Q)
Colour fastness to perspiration	PASS (Meets the requirement)	Quality (R_Q)

Impact Resistance and Toughness	PASS (Meets the requirement)	Functionality ($R_{F)}$
Load Carrying capacity	PASS (Meets the requirement)	Functionality ($R_{F)}$
pH	PASS (Meets the requirement)	Human Safety (R_{HI})
Formaldehyde	PASS (Meets the requirement)	Human Safety (R_{HI})
Waterproof	PASS (Meets the requirement)	Functionality ($R_{F)}$
Air permeability	PASS (Meets the requirement)	Functionality ($R_{F)}$
Water Vapour Permeability	PASS (Meets the requirement)	Functionality ($R_{F)}$

Table 8-6 Linkage of outputs to Input -3

Test	Range	Pass/Fail Criteria
Material Composition / Fibre Content	No Range	If it meets the declaration (+ / - 5%)-PASS ($R_{\mathbf{Q}}$) Does not meet the declaration(+ / - 5%)-FAIL
Tensile strength and elongation of material	1. Tensile Strength- 60N-766.1N 2. Elongation-3.2mm-340.6mm	<50% Fail >50% Pass ($R_{\mathbf{F}}$)
Tear strength	0.5-45 N	<50% Fail >50% Pass ($R_{\mathbf{F}}$)
Bursting strength	11.9-125 PSI	<50% Fail >50% Pass ($R_{\mathbf{F}}$)
Impact Strength	Absolute Maximum Capacity: 1-5 Cycles; Weight- 2-5 kgs. Comparative maximum Capacity: 0-5 Cycles; Weight-3 kgs.	<50% Fail >50% Pass ($R_{\mathbf{F}}$)
Load Bearing	4-35 kgs.	<50% Fail >50% Pass ($R_{\mathbf{F}}$)
Thickness	0.044- 0.98 mm	<50% Fail >50% Pass ($R_{\mathbf{F}}$) ($R_{\mathbf{Q}}$)
Weight	39.7 -368.3 g/m^2	If it meets the declaration (+ / - 10%)-PASS ($R_{\mathbf{Q}}$) ($R_{\mathbf{F}}$) Does not meet the declaration(+ / - 10%)-FAIL
Air permeability	0-789 mm/s	<50% Fail >50% Pass ($R_{\mathbf{F}}$)
Water Vapour Permeability	14.3 -1003.6 g/m^2.day	<50% Fail >50% Pass ($R_{\mathbf{F}}$)
pH	5.92 -9.12	4-9 Pass ($R_{\mathbf{HI}}$) <4 and >9 Fail (GB 18401, 2010)

Formaldehyde	5.86-14.06 mg/ kg	< or equal to 300 Pass(R_{HI}) >300 Fail (GB 18401, 2010)
Colour fastness to light	4	3 and >3 Pass(R_{HI}) (R_Q) <3 Fail
Colour fastness to friction	3-4 – 4-5 (3.5-4.5)	3 and >3 Pass(R_{HI}) (R_Q) <3 Fail (GB 18401)
Colour fastness to washing	4-4.5	3 and >3 Pass(R_{HI}) (R_Q) <3 Fail
Colour fastness to perspiration	Acid: 4-4.5 Alkaline: 4-4.5	3 and >3 Pass(R_{HI}) (R_Q) <3 Fail (GB 18401, 2010)
Colour fastness to water	4-4.5	3 and >3 Pass(R_{HI}) (R_Q) <3 Fail (GB 18401, 2010)

Table 8-7 Range of values of various tests and pass/fail criteria for input-3

4. Ecological properties

Table 8-8 describes how input no.4 is linked to the relevant outputs, i.e. human toxicity, environmental impact and 3R's. Table 8-9 shows the range of values of different tests obtained from Chapter 7 and the pass/fail criteria for various tests.

Test	Criteria	Output
Biodegradation of material	PASS (Meets the requirement)	Reduced Human Toxicity (R_{HI}) Lesser Environmental Impact(R_{EI})
Reusability	PASS (Meets the requirement)	Reduced Human Toxicity (R_{HI}) Lesser Environmental Impact(R_{EI}) 3Rs (R_{3Rs}) - Reusability
Recyclability	PASS (Meets the requirement)	Reduced Human Toxicity (R_{HI}) Lesser Environmental Impact(R_{EI}) 3Rs (R_{3Rs}) - Recyclability

Table 8-8 linkage of outputs to Input-4

Test	Range	Pass/Fail Criteria
Biodegradation of material	Weight Loss: 1.42%-100% Tensile Strength Reduction: 1.36%-100%	Weight Loss: >50% Pass (R_{HI}) (R_{EI}) <50% Fail Tensile Strength Reduction: >50% Pass (R_{HI}) (R_{EI}) <50% Fail
Reusability	Absolute Maximum Capacity: 3.7-100 Cycles; Weight- 4-35 kgs. Comparative maximum Capacity: 0-500 Cycles; Weight-10 kgs.	<50% Fail >50% Pass ($R_{3R's}$) (R_{EI}) (R_{HI})
Recyclability	Shown Below. (RPIRank-1-10)	1-5 PASS ($R_{3R's}$) (R_{EI}) (R_{HI}) 6-10 FAIL

Table 8-9 Range of values of various tests and pass/fail criteria for input-4

8.2.3. Conclusive result

Three steps are required to arrive at the final result. The first step is to integrate quality and functionality to obtain the combined result (R_{QF}). The second step is to integrate human toxicity, environmental impact and the 3Rs to obtain the combined result (R_{EI}). The last step is to combine R_{QF} and R_{EI} to achieve $R_{Product}$, which is the ultimate, desired result from this developed eco-functional model. From the final result of $R_{Product}$, it is possible to determine the position of any textile product /shopping bag in terms of its eco-functionality.

1. Quality & functionality

Table 8-10 explains how quality and functionality are connected to obtain R_{QF}.

Rule No.	IF	Operand	R_Q / R_F		R_{QF}
1	R_Q is PASS	AND	R_F is PASS		GOOD
2	R_Q is PASS	AND	R_F is FAIL		POOR

3	R_F is PASS	AND	R_Q is FAIL	**THEN**	AVERAGE
4	R_Q is FAIL	AND	R_F is FAIL		POOR

Table 8-10 Quality and Functionality

2. 3Rs, environmental impact and human impact

Table 8-11 explains the connections among the 3Rs, environmental impact and human impact to obtain R_{EIF}.

Rule No.	**IF**	$\mathbf{R_{EI}}$	$\mathbf{R_{HI}}$		$\mathbf{R_{EIF}}$
1	R_{3Rs} is PASS	R_{EI} is PASS	R_{HI} is PASS	**THEN**	GOOD
2	R_{3Rs} is FAIL	R_{EI} is FAIL	R_{HI} is FAIL		POOR
3	R_{3Rs} is PASS	R_{EI} is FAIL	R_{HI} is FAIL		POOR
4	R_{3Rs} is FAIL	R_{EI} is PASS	R_{HI} is FAIL		POOR
5	R_{3Rs} is FAIL	R_{EI} is FAIL	R_{HI} is PASS		POOR
6	R_{3Rs} is PASS	R_{EI} is PASS	R_{HI} is FAIL		AVERAGE
7	R_{3Rs} is FAIL	R_{EI} is PASS	R_{HI} is PASS		AVERAGE
8	R_{3Rs} is PASS	R_{EI} is FAIL	R_{HI} is PASS		AVERAGE

Table 8-11 3Rs, Environmental Impact, Human Impact

3. Overall result

Table 8-12 shows how the overall result is arrived at by combining R_{EIF} and R_{QF} obtained from the previous two steps. Table 8-13 lists the decision criteria followed for various conditions.

Rule No.	**IF**	**Operand**	$\mathbf{R_{EIF} / R_{QF}}$		$\mathbf{R_{Product}}$
1	R_{QF} is GOOD	AND	R_{EIF} is GOOD	**THEN**	PASS
2	R_{QF} is GOOD	AND	R_{EIF} is POOR		FAIL
3	R_{QF} is AVERAGE	AND	R_{EIF} is POOR		FAIL
4	R_{QF} is AVERAGE	AND	R_{EIF} is AVERAGE		MEDIUM
5	R_{EIF} is AVERAGE	AND	R_{QF} is POOR		FAIL
6	R_{QF} is GOOD	AND	R_{EIF} is AVERAGE		PASS
7	R_{QF} is POOR	AND	R_{EIF} is GOOD		FAIL
8	R_{QF} is AVERAGE	AND	R_{EIF} is GOOD		PASS
9	R_{QF} is POOR	AND	R_{EIF} is POOR		FAIL

Table 8-12 Overall result

Condition	Decision Criteria (All of the conditions to be fulfilled)
R_Q is PASS	✓ Material Composition / Fibre Content & gsm pass
R_F is PASS	✓ Tensile strength pass ✓ Colour fastness to water pass ✓ Colour fastness to perspiration (Acid and Alkali) pass ✓ Colour fastness to washing pass ✓ Colour fastness to friction pass ✓ Tear strength pass ✓ Bursting strength pass ✓ Impact Strength pass ✓ Water Vapour Permeability pass
R_{3Rs} is PASS	✓ Reusability pass ✓ Recyclability Pass
R_{EI} is PASS	✓ R_{EI} is Close to none, Very less, less, moderately less and moderate. ✓ Biodegradation of material is pass ✓ Carbon footprint pass ✓ Ecological Resources footprint pass ✓ Environmental Load Unit-Emissions Pass
R_{HI} is PASS	✓ R_{HI} is Close to none, Very less, less, moderately less and moderate. ✓ pH Pass ✓ Formaldehyde Pass ✓ Biodegradation of material is pass ✓ Human Toxicity Pass

Table 8-13 Decision Criteria

8.3. Derivation of eco-functional index

As discussed in Chapter 3, with the aid of the developed eco-functional model, it is possible to derive an eco-functional index/score of any textile product in addition to evaluating the capacity of any product to sustain the requirements of the eco-functional assessment. The steps to arrive at the final eco-functional index are discussed below (Li et al., b).

1. Fibre /raw material

In the first step, only one index is derived, which is the ecological sustainability index (ESI). This index is derived based on the results of ESIR given in Table 8-1. The grading system for ESI is given below in Table 8-14.

ESI	Index
1-2	5
3-4	4
5-6	3
7-8	2
9-10	1

Table 8-14 Grading system for ESI

2. Process of manufacture

For the second input, two indices (human toxicity index (HTI) and environmental impact index (EII)) are proposed and their definitions are given below. Environmental impact index is further derived from the indices of carbon footprint, ecological resource footprint and environmental load unit. The grading system for arriving at HTI and EII are tabulated in Table 8-15.

Indices

[1] Human toxicity index (HTI)

[2] Environmental impact index (EII) = ∑CFPI + ERFPI+ELUI

- *Carbon footprint index (CFPI)*
- *Ecological resources footprint index (ERFPI)*
- *Environmental load unit index (ELUI)*

Human toxicity index		Carbon footprint index	
<20%	5	<20%	5
20.1-40%	4	20.1-40%	4
40.1-60%	3	40.1-60%	3
60.1-80%	2	60.1-80%	2
80.1-100%	1	80.1-100%	1

Ecological resources footprint index		Environmental load unit index	
<20%	5		
20.1-40%	4	<20%	5
40.1-60%	3	20.1-40%	4
60.1-80%	2	40.1-60%	3
80.1-100%	1	60.1-80%	2
		80.1-100%	1
Environmental impact index			
13-15	**5**		
10-12	**4**		
7-9	**3**		
4-6	**2**		
<3	**1**		

Table 8-15 Grading system for HTI and EII

3. Functional properties

For the third input, i.e. functional properties of the product, only one index (Functionality index (FI)) is proposed. This is the resultant index of many sub indices, which are discussed below in Tables 8-16 – 8-19. The grading system for arriving at FI is tabulated in Table 8-20.

Indices

- *Strength index(SI)*
- *Impact resistance index(IRI)*
- *Human safety index(HSI)*
- *Permeability index(PI)*
- *Colour fastness index(CFI)*
- *Quality index(QI)*
- *Functionality index(FI) = ∑QI + SI+HSI+ PI+CFI+IRI*

Strength index (SI)

Tensile strength index 80.1-100% 5 60.1-80% 4 40.1-60% 3 20.1-40% 2 <20% 1	Tear strength index 80.1-100% 5 60.1-80% 4 40.1-60% 3 20.1-40% 2 <20% 1
Bursting strength index 80.1-100% 5 60.1-80% 4 40.1-60% 3 20.1-40% 2 <20% 1	**Strength index =** ∑ Tensile strength index + Tear strength index + Bursting strength index

Table 8-16 Grading system for strength index

Human safety index

pH index 4-9 5 <4 1 Formaldehyde index <300 5 >300 1	**Human safety index =** ∑ pH index + Formaldehyde index

Table 8-17 Grading system for human safety index

Permeability index

Air permeability index 80.1-100% 5 60.1-80% 4 40.1-60% 3 20.1-40% 2 <20% 1	Water vapour permeability index 80.1-100% 5 60.1-80% 4 40.1-60% 3 20.1-40% 2 <20% 1
Permeability index = ∑ Air permeability index + Water vapour permeability index	

Table 8-18 Grading system for permeability index

Colour fastness index

Colour fastness index		**Colour fastness index =** ∑ Colour fastness to rubbing index + Colour fastness to light index + Colour fastness to water index + Colour fastness to washing index + Colour fastness to Alkali Perspiration index + Colour fastness to Acid Perspiration index
5	5	
4-5	4	
3-4	3	
2-3	2	
<2	1	

Table 8-19 Grading system for colour fastness index

Functionality index

Strength index		Impact resistance index	
13-15	5	>5	5
10-12	4	4	4
7-9	3	3	3
4-6	2	2	2
<3	1	1	1
Human safety index		**Permeability index**	
10	5	9-10	5
6	3	7-8	4
2	1	5-6	3
		3-4	2
		1-2	1
Colour fastness index		**Quality index (Material composition and Weight (GSM))**	
26-30	5		
21-25	4	Pass	5
16-20	3	Fail	1
11-15	2		
<10	1		

Functionality index	
26-30	**5**
21-25	**4**
16-20	**3**
11-15	**2**
<10	**1**

Table 8-20 Grading system for Functionality index

4. Ecological properties

For the final input, i.e. ecological properties of the product, an ecological index (ECI) is proposed. This is the resultant index of other three sub indices, which are discussed below in Table 8-21. The grading system for arriving at EI is shown in Table 8-21.

Indices

- *Biodegradability index(BI)*
- *Reusability index(RUI)*
- *Recyclability index (RCI)*
- *Ecological index(ECI) = ∑ BI + RUI+ RC*

Biodegradability index		Reusability index	
80.1-100%	5	>401	5
60.1-80%	4	301-400	4
40.1-60%	3	201-300	3
20.1-40%	2	101-200	2
<20%	1	0-100	1
Recyclability index		**Ecological index**	
1-2	5	**13-15**	**5**
3-4	4	**10-12**	**4**
5-6	3	**7-9**	**3**
7-8	2	**4-6**	**2**
9-10	1	**<3**	**1**

Table 8-21 Grading system for Ecological index

5. Eco-functional index

The final result, eco-functional index is a result of the aggregation of the individual scores/indices of each input and is defined below:

Eco-functional index = ∑ESI + HTI + EII +FI+ECI,

Where ESI = Ecological sustainability index

EII = Environmental impact index

HTI = Human toxicity index

FI= Functionality index

ECI= Ecological index

The grading system for quantifying eco-functional index is tabulated in the following Table 8-22.

Eco-functional index	
21-25	**5**
16-20	**4**
11-15	**3**
6 -10	**2**
<5	**1**

Table 8-22 Grading system for Eco-functional index

8.4. Eco-functional assessment of various shopping bags

To execute the eco-functional assessment of various shopping bags under consideration, a computer programme was written using Microsoft Visual C++ 2008 Express Edition. An interface was created to connect the four inputs discussed previously with all the rules for assessment of the shopping bags in eco-functional terms (as discussed in section 8.1) and deriving the eco-functional index/score (as discussed in section 8.2). The results of eco-functional assessment including index scores are tabulated in Table 8-23.

From Table 8-23, it can be seen that none of the bags considered for this present study is able to meet the requirements of the eco-functional assessment stipulated in this study's developed model (listed in Tables 8-1- 8-13).

Sample No. & Name	ESI	HTI	EII	FI	ECI	EFI	EFS/25	$R_{Product}$
1. Paper 40g	5	5	5	2	4	5	21/25	Fail
2. Paper 75g	5	5	5	2	4	5	21/25	Fail
3. Paper 150g	5	5	5	3	4	5	22/25	Fail
4. Cotton -1	4	3	3	5	4	4	19/25	Fail
5. Cotton -2	5	1	1	5	4	4	16/25	Fail
6. HDPE -1	2	5	5	2	4	4	18/25	Fail
7. HDPE -2	2	5	5	2	4	4	18/25	Fail
8. HDPE -3	2	5	5	2	4	4	18/25	Fail
9. LDPE -1	2	5	5	3	3	4	18/25	Fail
10. LDPE -2	2	5	5	3	4	4	19/25	Fail
11. LDPE -3	2	5	5	3	4	4	19/25	Fail
12. PP 40g Sewn	1	5	5	4	4	4	19/25	Fail
13. PP 75g Sewn	1	5	5	5	4	4	20/25	Fail
14. PP 100g Sewn	1	5	5	5	4	4	20/25	Fail
15. PP 40g Thermo	1	5	5	4	4	4	19/25	Fail
16. PP 75g Thermo	1	5	5	5	4	4	20/25	Fail
17. PP 100g Thermo	1	5	5	5	4	4	20/25	Fail
18. PET 40g Sewn	3	5	5	4	4	5	21/25	Fail
19. PET 75g Sewn	3	5	5	5	4	5	22/25	Fail
20. PET 100g Sewn	3	5	5	5	4	5	22/25	Fail
21. PET 40g Thermo	3	5	5	3	3	4	19/25	Fail
22. PET 75g Thermo	3	5	5	4	4	5	21/25	Fail
23. PET 100g Thermo	3	5	5	5	4	5	22/25	Fail

Table 8-23 Eco-functional scores and assessment results

Regarding paper bags in the low, medium and heavy weight categories, though none of them could meet the requirements of functionality part, they scored very well in terms of environmental impact in terms of both raw materials and manufacturing process. Their environmental impact and ecological sustainability values with respect to raw materials, carbon and ecological footprints and also other LCA indices are impressive and they earned the maximum scores. They earned good scores even for their ecological properties (due to better biodegradation and recyclability indices, though their reusability values are the lowest); hence they achieved the maximum index scores compared to all of their counterparts. If they were bestowed with higher functionality, which could also enable them to be reused many times, they would have met all the requirements of this eco-functional assessment and met the eco-functional requirements.

Concerning woven bags, the medium weight cotton bag (cotton-1), earned the maximum index score in functionality, as expected. ESI and ecological values of this sample are also better. However, its LCA indices are very minimal; hence it obtained the next lowest index score in the samples list for this study. Cotton bags of heavy weight (cotton-2) are a blended composition (Polyester and Cotton and due to its mixed composition with PET, its ESI values are also less and LCA indices and ecological values are similar to cotton-1. Both types of cotton bag performed well in biodegradability, next to paper bags and out rated all the samples as far as reusability is concerned. Hence they scored well in the ecological area despite their lower recyclability index values. Cotton-2 sample earned the lowest index score out of all the samples considered in this study.

As regards plastic bags, HDPE and LDPE of low, medium and heavy weight, they scored almost the same values in the ESI and LCA indices. They scored the maximum points in LCA indices in this samples list. Their functional and ecological indices are almost the same except for slight differences caused by functionality and reusability differences owing to the GSM of different samples. Their ESI values are lower due to the raw materials environmental issues.

With respect to nonwoven bags made out of Polypropylene (PP) and Polyester (PET) manufactured by sewn and thermo bonded technologies, Polypropylene, by virtue of environmental issues related to its raw material, scored poorly in ESI and polyester appears to be slightly better in this category than PP. Their LCA indices are almost the same for different areal densities and also their functional and ecological values are very close. But comparing on similar grounds, PP seems to be better than PET in functional and reusability considerations. Also sewn bags are comparatively better than thermo bonded ones. In eco-functional terms, PET outscores PP, and PET bags gained second best position to paper bags in this list of samples.

From the eco-functional assessments, it is very clear that eco-functional assessment needs to consider many aspects and a material should ideally satisfy all the requirements to the maximum, and if not, then at least meet the average requirement. Recently, norms have become very stringent, and they have to be strict to mitigate urgent environmental issues. Also each and every aspect of functional, ecological and other aspects needs focused attention. None of the aspects can be overlooked, for instance, a quality parameter such as the discrepancy between the actual and declared

GSM and fibre content calls for attention. This model includes serious consideration of almost all the essential eco-functional considerations.

Since there are currently available criteria to evaluate the status of shopping bags in terms of the aspects discussed in this study, the current research considered the 50% value of the maximum scores obtained from the whole list of samples. In future, a huge database needs to be developed for the whole range of materials, including shopping bags, so that decisions can be made according to the requirements of society and the different views and arguments of various stakeholders. Probably the point of decision may be moved to 70 or 80% in the future, say in 10 years time to benefit the environment.

8.5 Eco-functional assessment combined with life cycle assessment (LCA)

The second part of this chapter deals with the comprehensive life cycle assessment study conducted to test various research questions formulated in Chapter 3. Plastic bags made out of HDPE, LDPE, paper, nonwoven bags made out of polypropylene and polyester and woven bags made out of cotton were considered for the study. LCA study was conducted for various shopping bags to assess the carbon, ecological footprints and eco-damage in each phase of their life cycles. Various steps in conducting a LCA study, i.e. goal and scope, life cycle inventory, life cycle impact assessment and life cycle interpretation for this study are discussed below.

8.5.1. Goal and scope definition

The goals of the present study are: 1. To collect the life cycle inventory data for each life cycle phase of plastic, paper, nonwoven and woven shopping bags. 2. To assess the life cycle impacts of various shopping bags by measuring the carbon, ecological footprints and eco-damage in each phase of their life cycles from raw material to disposal states in Mainland China, Hong Kong and India. By means of this assessment, the influence of each phase of life cycle on the final impact result will be determined to test the four research questions proposed in Chapter 3.

Life cycle inventory data were collected for raw materials and manufacturing phase from secondary data sources. For raw material, energy, water needs and the GHG emissions during fibre manufacturing phase were considered. In the manufacturing phase, energy inputs and GHG emissions during the manufacturing phase were considered. Areas apart from the consideration of the secondary sources from where the data for this study were obtained are the boundaries of this study. For use and disposal values, a questionnaire survey was conducted among different user groups in Mainland China, Hong Kong and India. From this study, values of reuse/recycle/disposal to landfill options were obtained for various shopping bags. Apart from these end-of-life scenarios, other scenarios are the boundaries of this study.

To derive the functional unit best suited to the three territories considered, the consumption statistics of shopping bags were obtained from the literature pertaining to Mainland China, Hong Kong and India. Among the four types of bags under consideration in this present study, statistics were readily available on the consumption of plastic bags. From the currently available statistics on shopping bags consumption, an average Chinese and a Hong Kong resident, on average uses 3 plastic bags per day (EPD, HK; Environmental News Network, 2008). Although there is no readily available statistics for the usage of plastic bags in India compared to Hong Kong and Mainland

China (Businessgreen.com, 2010; The Times of India), it is estimated that India's per capita consumption is 150 plastic bags a year (Online Edition of The Hindu, 2010).

The functional unit of this present study is the "number of shopping bags used for grocery shopping per year by an average Chinese/Indian/HK resident". For the territories considered in this study, we assume that plastic (HDPE) and paper bags are comparable and they are equivalent to each other in functional terms. For nonwoven and woven bags, we assume that 1 nonwoven and 2 woven cotton bags will replace 100 single use plastic (HDPE) and paper bags. Further, these assumptions can be validated from the relevant literature also (Nolan ITU et al., 2002; ExcelPlas Australia et al., 2004; James and Grant, 2005; Reusable shopping bags; Envirosax; Alburyenvirobags). From the above studies, it is understood that 1.3 LDPE bags equal 1 HDPE and 1 paper bag. Hence 1095 plastic (HDPE) and paper bags, 1432.5 LDPE bags, 10.95 nonwoven and 21.9 woven bags are required to fulfill the functional unit assumed for this study for average Chinese and HK residents. For Indians, 150 plastic (HDPE) and paper bags, 195 LDPE bags, 1.5 nonwoven and 3 woven bags are needed to fulfill this study's functional unit (Muthu et al., 2011).

8.5.2. Life cycle inventory

Raw material phase

LCI data for raw material phase was discussed in detail in Chapter 4. Tables 4-1 - 4-3 listed the essential details of this phase. Data shown in Table 4-1 – 4-3 were utilized to model the scenario for raw material phase to test research question 1.

Manufacturing phase

Chapter 5 was devoted to the LCI data for the manufacturing phase. Tables 5-1-5-3 listed the essential aspects of LCI of different shopping bags as far as their manufacturing phase is concerned. Data shown in those tables were utilized to model the scenario of the manufacturing phase of different shopping bags according to the functional unit of the study in the three territories to test research question 2.

Use and disposal phases

As discussed earlier, usage and disposal of different shopping bags rest solely in the hands of consumers. To determine usage and disposal attitudes, a questionnaire survey was conducted among different user groups of shopping bags in Mainland China, HK and India and the details of this were discussed in detail in Chapter 6. Usage and disposal details of different shopping bags according to the perception of consumers were considered at this juncture to model the usage and disposal values of various shopping bags (see Table 8 -24).

Options in %	Plastic (HDPE)			Plastic (LDPE)			Paper			Nonwoven (PP)			Nonwoven (PET)			Woven Cotton		
	CH	HK	IN	CH	HK	IN	CH	HK	IN	CH	HK	IN	CH	HK	IN	CH	HK	IN
Recycle	24	21	33	24	21	33	46	45	47	33	27	29	33	27	29	32	27	26
Reuse	32	30	31	32	30	31	32	38	22	49	54	44	49	54	44	53	53	53
Landfill	44	49	36	44	49	36	22	17	31	18	19	27	18	19	27	15	20	21

Table 8-24 LCI of use and disposal phases – Consumer perception

Table 8-24 presents the details of consumer's perception of usage and disposal of various shopping bags. These values need to be reexamined in the light of the experimental results of various functional, eco-functional and ecological properties of different shopping bags discussed in Chapters 6 and 7. This needs to be done to test the research questions 3 and 4. Hence three different scenarios are constucted at this juncture:

1. Scenario 1- Baseline scenario – Life cycle assessment of shopping bags from consumers' perceptions.
2. Scenario 2- Functionality influenced scenario – Life cycle assessment of shopping bags from consumers' perceptions influenced by the functional and eco-functional considerations.
3. Scenario 3- Recyclability and biodegradability influenced scenario – Life cycle assessment of shopping bags from consumers' perceptions influenced by the recyclability and biodegradability of different shopping bags.

Table 8-25 presents an overview of a range of the various functional and eco-functional properties of different shopping bags discussed in Chapter 6. Among the properties, certain earmarked properties that infleunce the life time of shopping bags to the maximum extent were chosen and reported in Table 8-25.

Alternative	Tensile Strength in Newton	Tear Strength in Newton	Bursting Strength in PSI	Weight-holding capacity@ 5 Mins.	Comparative Reusability @ 10 kgs.	Comparative impact strength @ 3 kgs.
Plastic bag (HDPE)	100-165	6-22.6	18-33	19-25	500 cycles	0 cycles
Paper Bag (Kraft)	196-270	0.6-1	19-24	4-7	0 cycles	0 cycles
Boutique plastic	60-109	0.5-3	11-21	13-20	300-500 cycles	0 cycles

(LDPE)						
Woven Cotton Bag	566-766	9.8-24.8	110-125	35	500 cycles	5 cycles
PP Nonwoven bag	127-249	16-45	28-70	14-25	500 cycles	0-5 cycles
PET Nonwoven bag	68-245	9.4-24	27-67	12-25	0-500 cycles	0-5 cycles

Table 8-25 Functional and Eco-functional properties of shopping bags – An Overview

From Table 8-25, it can be seen that cotton bags showed remarkable strength and eco-functional characteristics and they top the whole list. They are followed by PP and PET nonwoven bags. Plastic and paper bags are next to reusable bags. In this category of single use, HDPE bags seem to be the best followed by LDPE and paper bags. If the data in Table 8-24 is reassessed in the light of the values given in Table 8-25, we can see that a certain percentage of reuse of various bags can definitely be altered. This is done at this juncture to test research question 3 and to build the details of Scenario 2. When the reuse shown in Table 8-24 is altered to keep recycling percentage constant, there may be a shift in the values of landfill options. From the results in Table 8-25, it is assumed that 100% of the landfill values of cotton bags can be diverted to reuse, 90% of PP nonwoven bags and 80% of PET nonwoven bags can be diverted from landfill option to reuse. As far as single use bags are concerned, 50% of HDPE, 40% of LDPE and 30% of paper can be diverted to reuse from landfill option. The resultant values are tabulated in Table 8-26.

Options in %	Plastic (HDPE)			Plastic (LDPE)			Paper			Nonwoven (PP)			Nonwoven (PET)			Woven Cotton		
	CH	HK	IN	CH	HK	IN	CH	HK	IN	CH	HK	IN	CH	HK	IN	CH	HK	IN

Recycle	24	21	33	24	21	33	46	45	47	33	27	29	33	27	29	32	27	26
Reuse	54	54	49	50	51	45	39	43	30	65	71	69	63	69	65	68	73	74
Landfill	22	25	18	26	28	22	15	12	23	2	2	2	4	4	6	0	0	0

Table 8- 26 LCI of functionality influenced use and disposal phases – Scenario 2

Scenario 3 deals with the recyclability and biodegradability values of shopping bags. Chapter 7 discussed these aspects in detail. A model was developed in Chapter 7 to quantify the recyclability values of various fibres and raw materials used for shopping bags. Recyclability Potential Index (RPI) of various raw materials was derived and various fibres and raw materials were ranked accordingly. From the results, the following order results in terms of RPI: PP, PET < HDPE < LDPE <Paper < Cotton. It is assumed that if recyclability does not meet requirements, the materials necessarily have to be diverted to landfills. At this juncture in the assumptions and the ranking order of RPI, it is assumed that the existing recyclability values listed in Table 8-24 [PP, PET keeping the same % of recycle, 90% for HDPE, 80% of LDPE, 70% Paper and 60% of cotton] can be reframed, keeping reuse as a constant. The resultant values are listed in Table 8-27.

Options in %	Plastic (HDPE)			Plastic (LDPE)			Paper			Nonwoven (PP)			Nonwoven (PET)			Woven Cotton		
	CH	HK	IN	CH	HK	IN	CH	HK	IN	CH	HK	IN	CH	HK	IN	CH	HK	IN
Recycle	22	19	30	19	17	26	32	32	33	33	27	29	33	27	29	19	16	16
Reuse	32	30	31	32	30	31	32	38	22	49	54	44	49	54	44	53	53	53
Landfill	46	51	39	49	53	43	36	30	45	18	19	27	18	19	27	28	31	31

Table 8-27 LCI of recyclability influenced use and disposal phases – Scenario 3

Another aspect that needs to be considered in Scenario 3 is biodegradability. From the results discussed in Chapter 7, it is understood that paper bags followed by cotton bags showed promising results. These two bags will be modeled with the option of excluding long term emissions using SIMAPRO version 7.3.

8.5.3. Life cycle impact assessment

With the LCI details discussed in the previous step, carbon footprint, ecological footprint and eco-damage were assessed in this step with the aid of SIMAPRO version 7.3. For calculating carbon footprint, IPCC 2007 GWP 100 a method of 1.01 version was used. IPCC 2007 is an update of the method IPCC 2001 developed by the Inter Panel on Climate Change. In this method, climate change factors of IPCC with a timeframe of 100 years have been chosen.

Regarding ecological footprint, ecological footprint method of 1.00 version was used. This method is directly taken from Ecoinvent 2.0 and includes the sum of time integrated direct land occupation and indirect land occupation to calculate the ecological footprint. Eco-damage was assessed by Eco-indicator'99 (2.06 version), a damage-oriented method with hierarchist perspective. Three damage categories were assessed by this method:

HH- Human Health (unit: DALY= Disability adjusted life years; this means different disability caused by diseases are weighted)

EQ-Ecosystem Quality (unit: PDF*m2yr; PDF= Potentially Disappeared Fraction of plant species)

R-Resources (unit: MJ surplus energy Additional energy requirement to compensate lower future ore grade).

LCI from previous step were processed for each territory separately to calculate the individual impact categories. The following figures illustrate the results of carbon footprint (Figs. 8-1 – 8-3), ecological footprint (Figs. 8-4 – 8-6) and eco-damage (Figs. 8-7 - 8-9) for Mainland China, Hong Kong and India.

From the results, it is understood that for the functional unit assumed for this study, the carbon, ecological footprints and eco-damage created by reusable bags were the lowest compared to single use bags. In the reusable bags, nonwoven bags made out of PP created the lowest impacts followed by PET and woven cotton bags in the three territories considered. Regarding single use bags, the impacts of HDPE were the lowest compared to paper and LDPE. Impacts created by LDPE are the highest in this comparative study. Also the impact of an average Indian are lower compared to that of Chinese and HK residents. This is very clearly evident from the size of the functional unit itself.

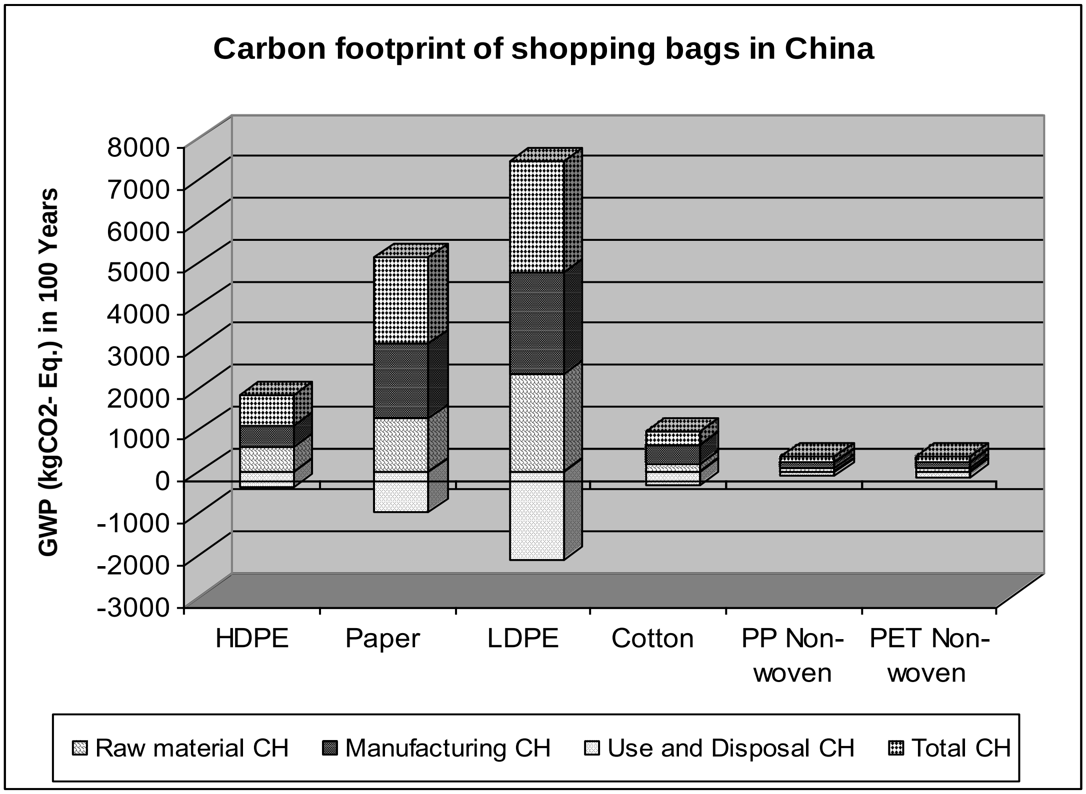


Figure 8-1 Carbon footprint results of Scenario 1 – Mainland China

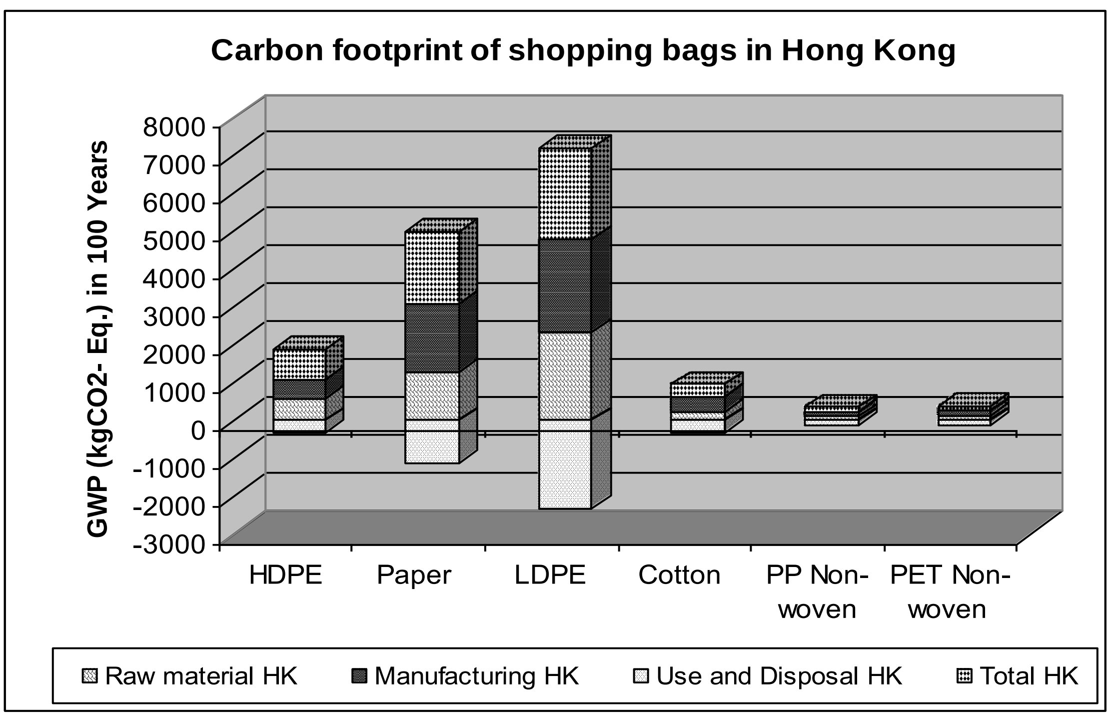


Figure 8-2 Carbon footprint results of Scenario 1 –Hong Kong

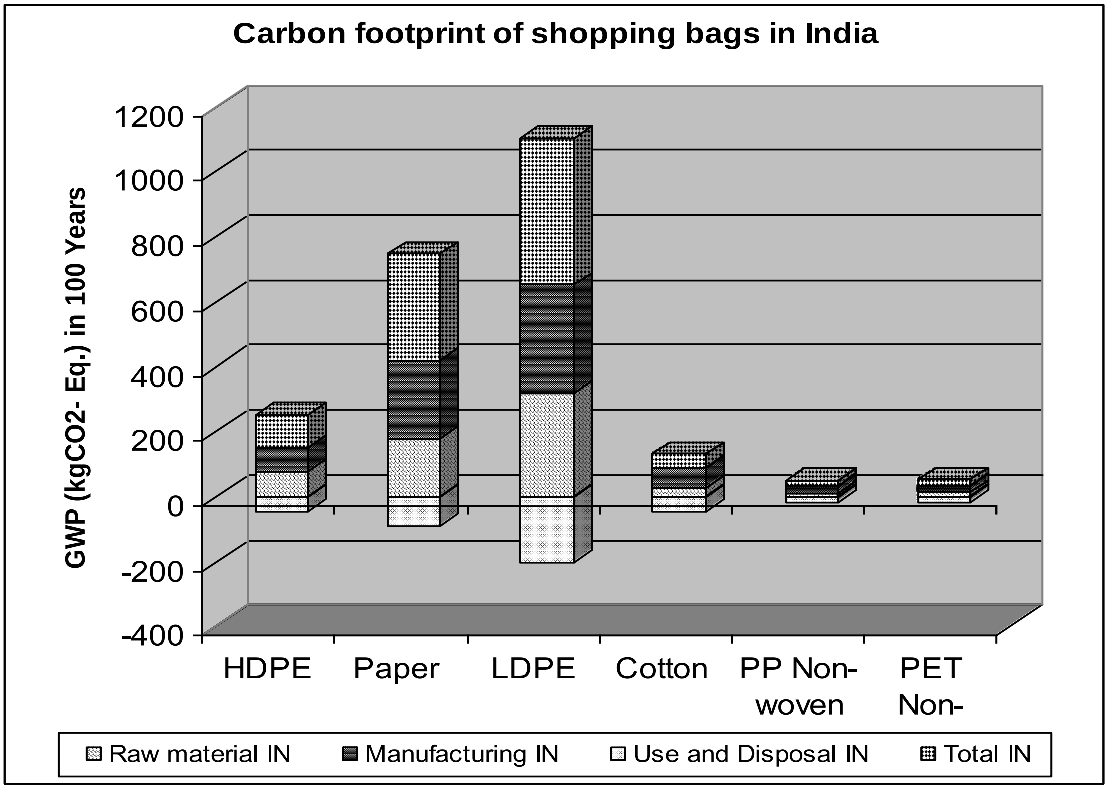


Figure 8-3 Carbon footprint results of Scenario 1 –India

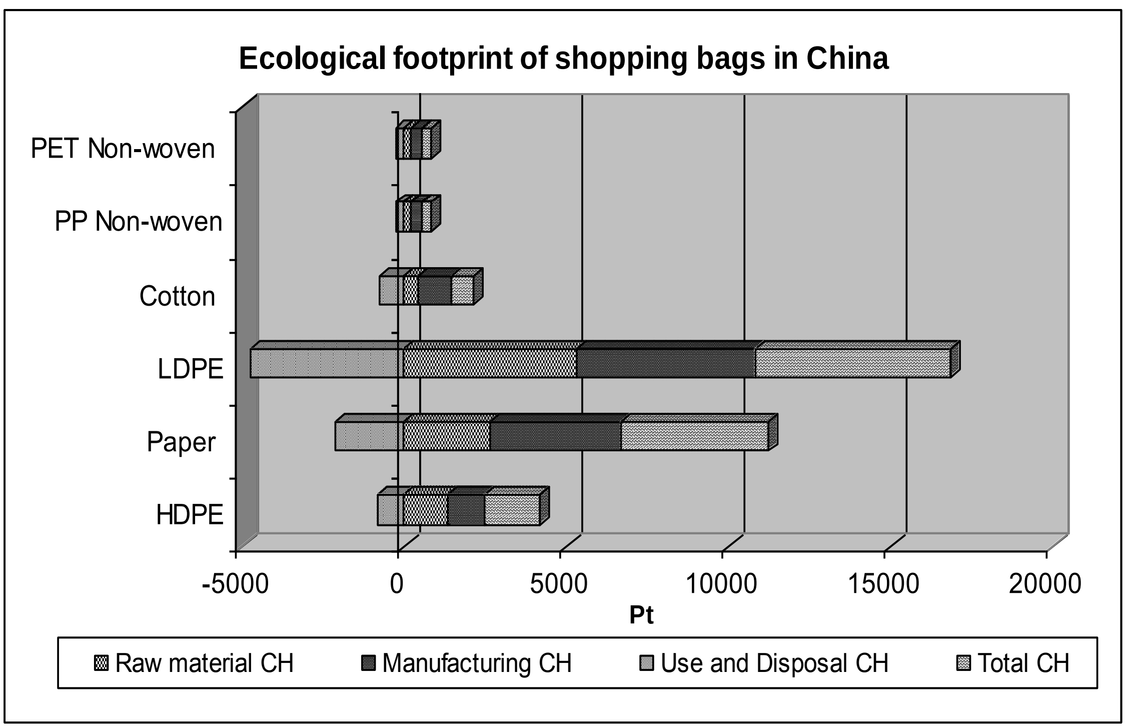


Figure 8-4 Ecological footprint results of Scenario 1 - Mainland China

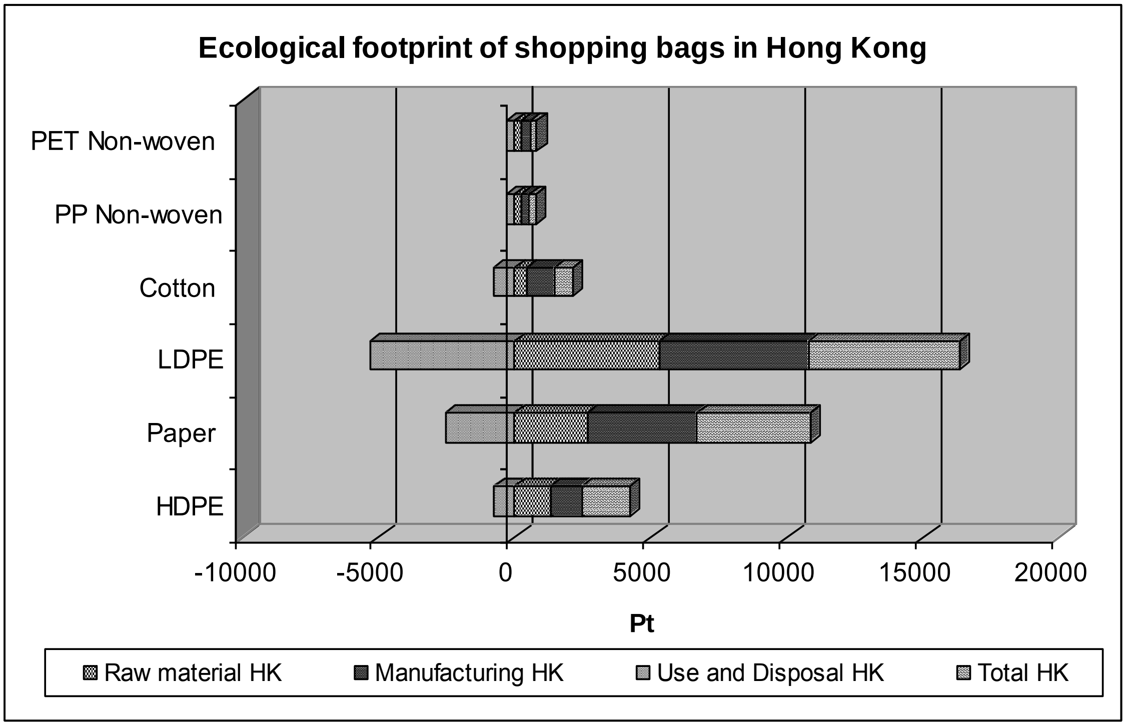


Figure 8-5 Ecological footprint results of Scenario 1 –Hong Kong

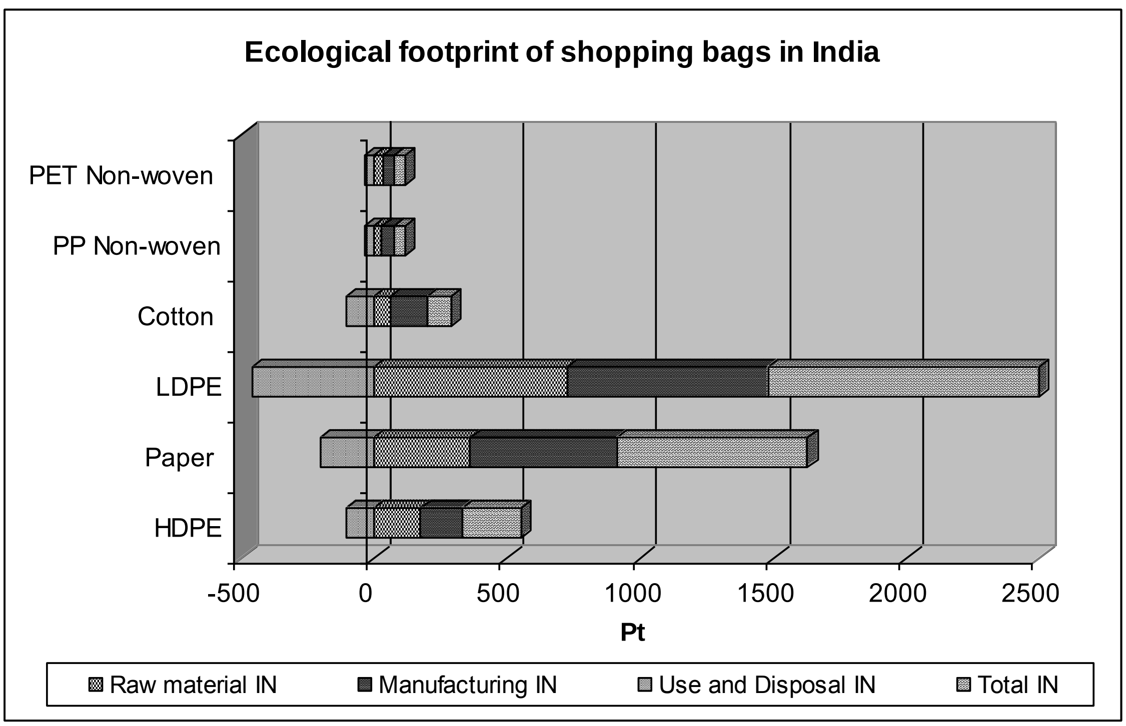


Figure 8-6 Ecological footprint results of Scenario 1 -India

Figure 8-7 Eco-damage results of Scenario 1 – Mainland China

Figure 8-8 Eco-damage results of Scenario 1 –Hong Kong

Figure 8-9 Eco-damage results of Scenario 1 –India

As illustrated in the above figures, each phase of the life cycle namely raw material, manufacturing, use and disposal impact the final result of LCA. Except HDPE, for all other shopping bags, manufacturing phase impacts are very high compared to the raw material phase. Due to the same functional unit values, impact results of raw material and manufacturing phase of Mainland China and HK are (and should be) the same. The real difference in the impact results must be contributed by consumption behaviour which is, in turn, explained by the use and disposal phases. If the impact results of Mainland China and HK are compared, for paper, PP and PET nonwoven bags, Chinese impacts are higher than HK ones, which can be attributed to the fact that the option of reuse was selected by more HK than Chinese residents. For LDPE and HDPE, though the same values were applied, the Chinese opted for a slightly higher proportion of reuse than HK residents, their HDPE's impact is lower than HK residents and their

LDPE's impact is higher, due to the higher functional unit size vis-à-vis the lower beneficial reuse option selected. Impacts of cotton bags are the same in both territories due to the almost similar end-of-life scenario values. These results are applicable to carbon, ecological footprints and eco-damage and pertain to the base line scenario- Scenario 1.

The life cycle impact assessment results of scenario 2, which is the functionality infleunced scenario, compared with the base line scenario are illustrated in Figs. 8-10- 8-12. From the results, it can be demonstrated that the functionality influenced scenario has reduced the impacts of carbon, ecological footprints and eco-damage to a significant extent. In this scenario, the key factor altered was the percentage of reuse, which brought down the impacts of different shopping bags enormously.

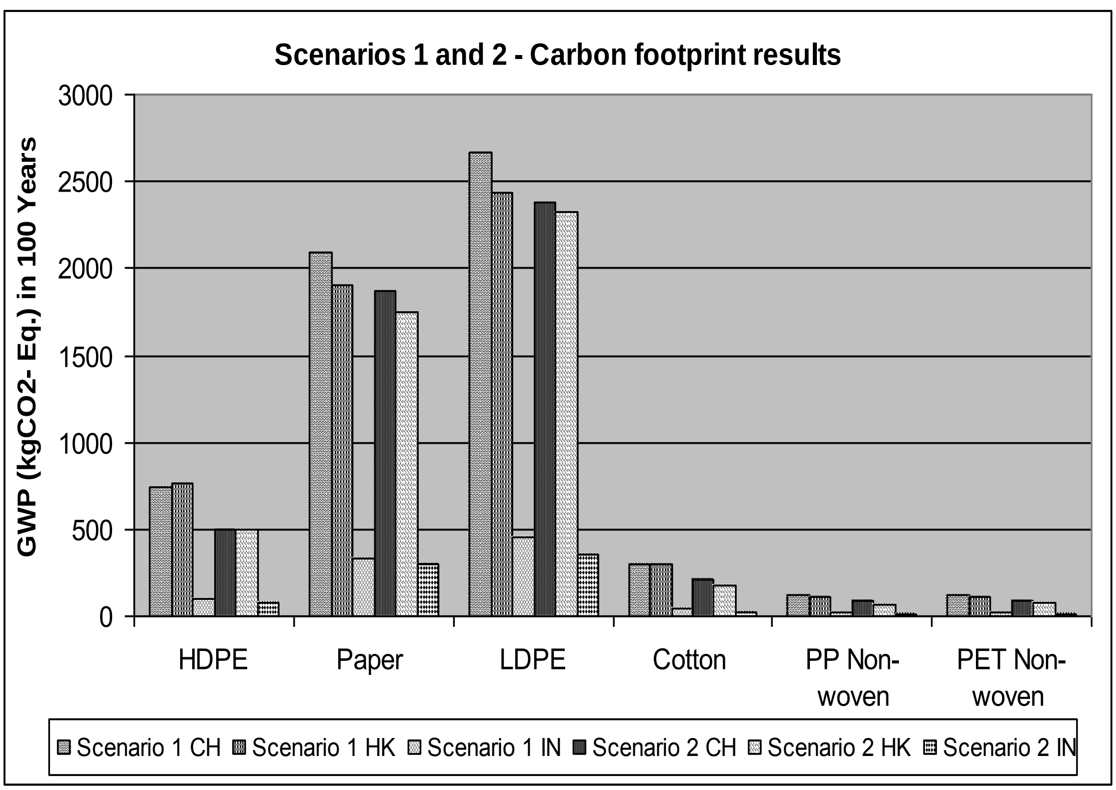


Figure 8-10 Scenarios 1 and 2- Carbon footprint

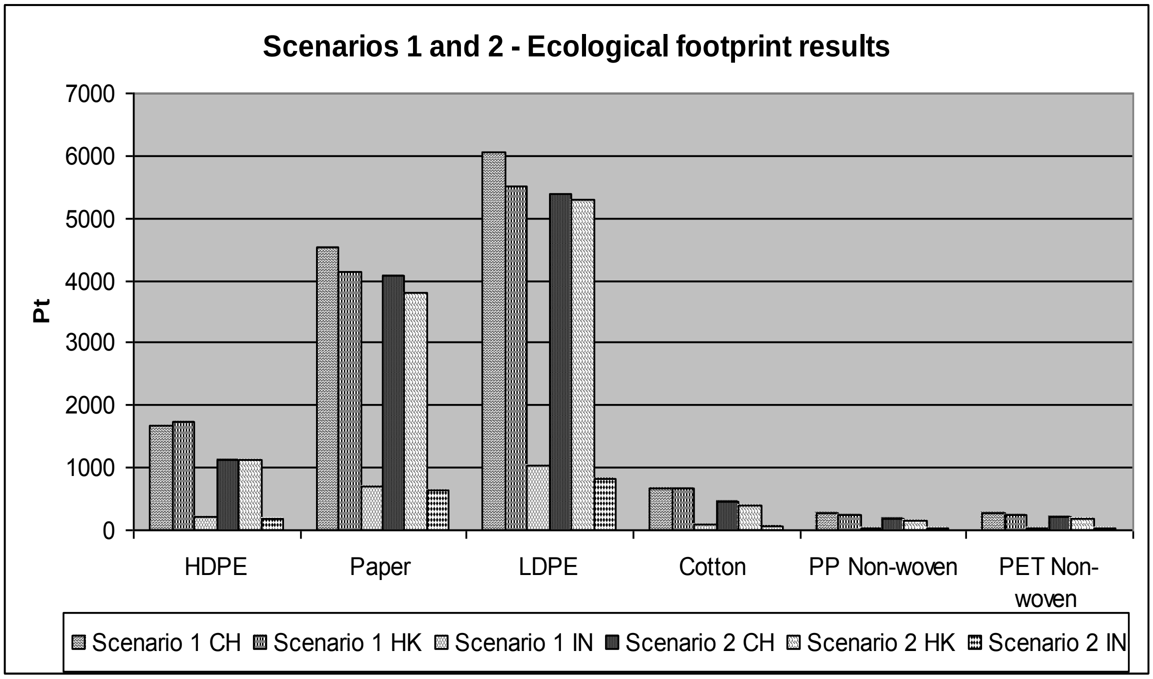


Figure 8-11 Scenarios 1 and 2- Ecological footprint

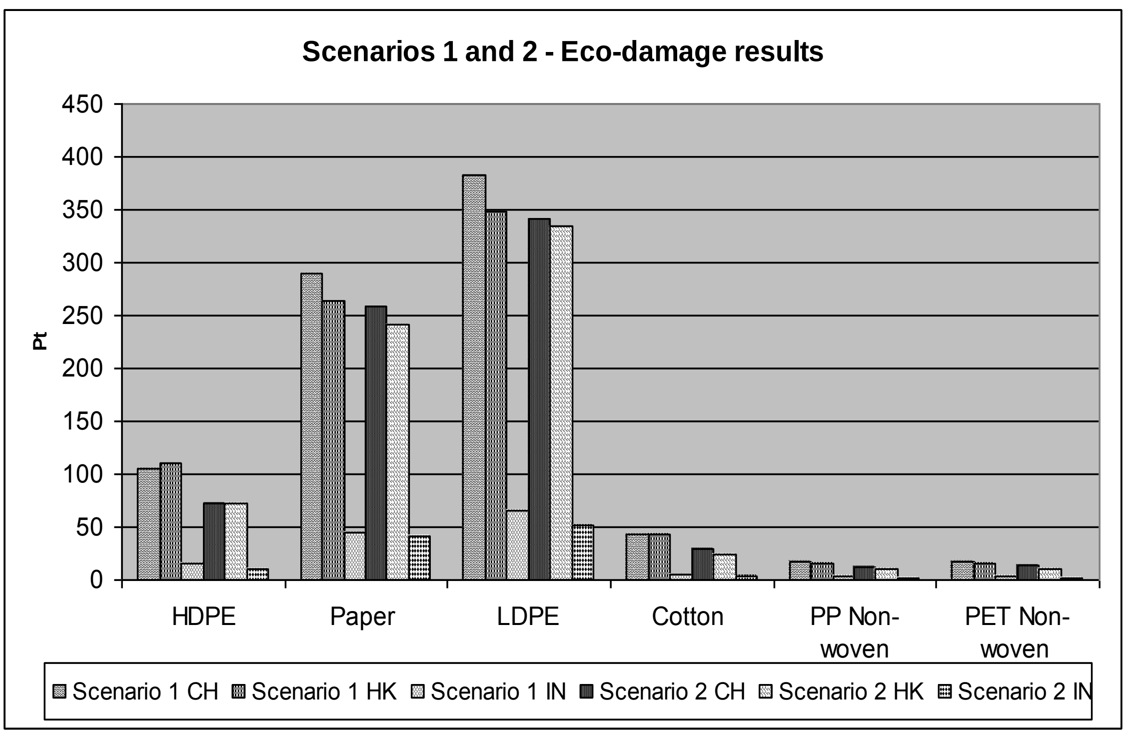


Figure 8-12 Scenarios 1 and 2- Eco-damage

The life cycle impact assessment results for scenario 3, which is the recyclability and biodegradability influenced scenario, are compared with the base line scenario in Figs. 8-13 – 8-15. From the results, it can be seen that PP, PET results are the same in both scenarios since the results did not change. HDPE's values were altered to 10% and the alteration did not influence the results. The results are the same in almost all the cases (except for ecological footprint in India), since the values altered are very small.

Though LDPE, paper values were altered to 20% and 30% respectively, paper results were not significantly influenced (in some of the categories results are not at all alltered at all), but the results of LDPE are influenced to a greater extent in all categories except in India, which may be due to the lower value of functional unit assumed. Instead of cotton's values altered to 40%, the impact results are again not influenced greatly and are the same in many instances.

It is understood that the changes in landfill percentage results do not greatly influence the results of some of the shopping bag materials, which could be due to the lower values assumed but may also be the due to the smaller size of functional unit assumed. Influence of biodegradation results were also modelled for cotton and paper, keeping the option of excluding the long term emissions. The results do not vary very much significantly and this could be attributed again to the smaller size of fcuntional unit assumed.

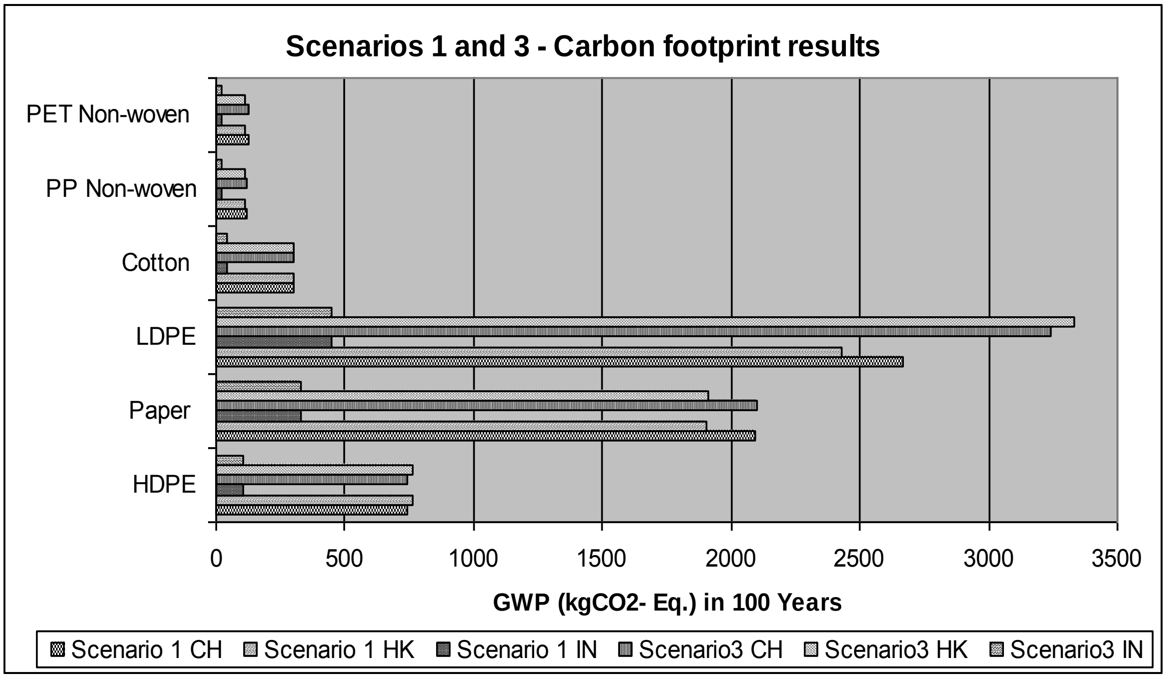


Figure 8-13 Scenarios 1 and 3- Carbon footprint

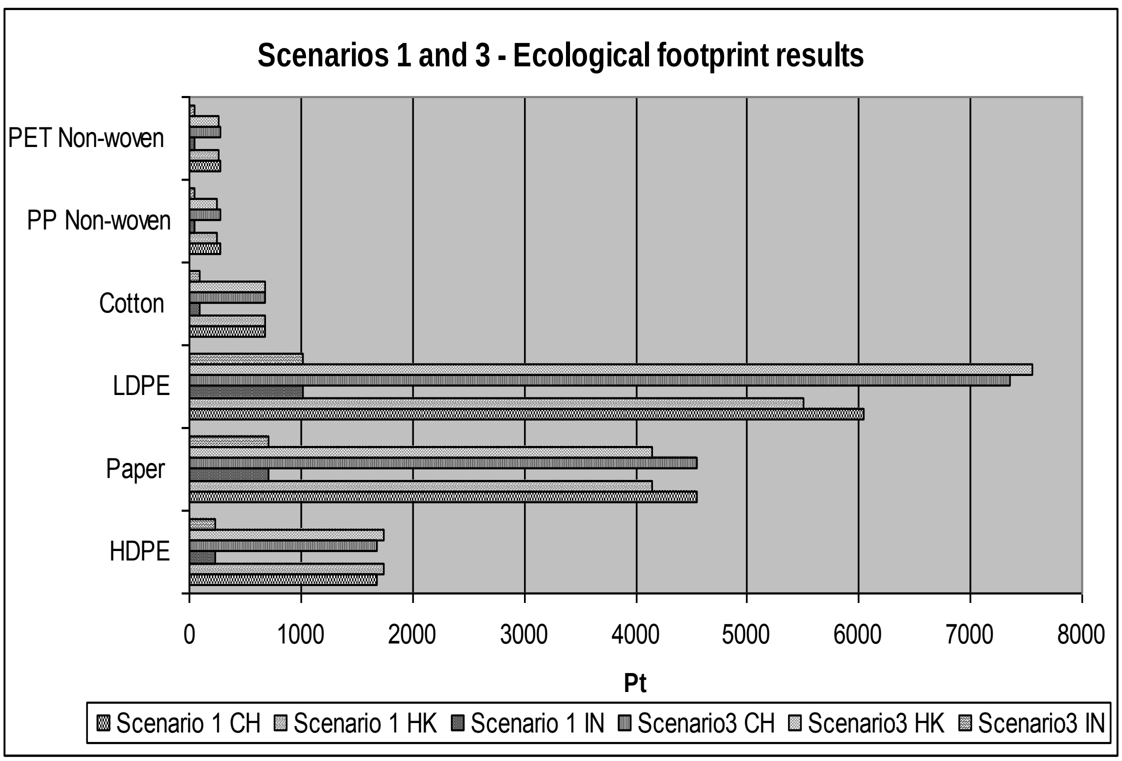


Figure 8-14 Scenarios 1 and 3- Ecological footprint

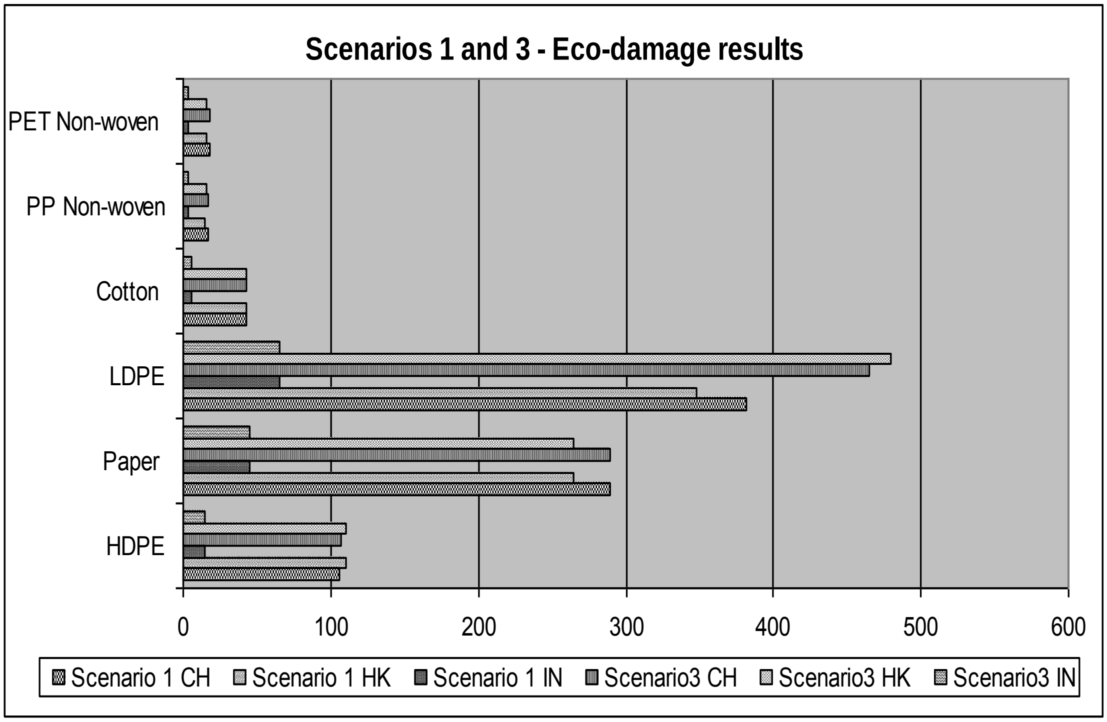


Figure 8-15 Scenarios 1 and 3- Eco-damage

8.5.4. Life cycle interpretation

Four research questions formed in this research work were presented in Chapter 3. Each phase in the life cycle namely raw material, manufacturing, use and disposal have clear influences on the results of the final impacts created by the shopping bags. It was shown that the PP nonwoven bags outscored all the shopping bags under consideration of the present study followed by PET and woven cotton bags. LDPE seems to be the least preferred option in terms of life cycle impacts.

Additionally, the consumption process influenced by the functionality characteristics of shopping bags also impacts the final results significantly. Different scenarios (Scenarios 1-3) were formed to test the research questions on the influence of functionality, recyclability and biodegradability. Scenario 1 was the baseline case, which was used to verify the influence of functionality (scenario 2), recyclability and biodegradability (scenario 3). From the results, it was understood that scenario 2 influenced the results for all shopping bags to a significant extent and scenario 3 did not influence the results as greatly as scenario 2 did. Though the reasons were pointed out for the least and most influencing scenarios, the key to interpretation lies in understanding the reduction in life cycle impacts of the shopping bags as changes in consumption behaviour aided by the functional and eco-functional properties possessed by the various shopping bags. Also it must be understood that the degree to which the percentage of reuse influences the final impact results is much higher than for the other end-of-life options, such as recycle and landfill.

It is a well-known fact that the greater the reuse of shopping bags, the lower the environmental impact will be. However the magnitude of importance needs to be revealed to expose consumers of shopping bags to reality. Even 1% more reuse of shopping bags would make a vast difference in terms of environmental impact. This has to be unveiled to the public if we want them to be educated in terms of environmental improvement. If we expect the public to appreciate environmental education in terms of their contribution to reducing environmental impact, they should be aware of such real values (Muthu et al., 2011).

Based on the above results and discussions, one important point to be noted here is that if any product is not reused till the end of its life, the concerns about environmental impact are huge. On the other hand if a product is not recycled and instead is sent to landfill, the eco-impact concerns become more acute. This can be clearly understood from the results of this study. So, usage and disposal of shopping bags assumes great significance in minimizing environmental impacts. If policies of these governments are reconsidered and recycling systems are encouraged and if they are appropriately placed, the number of recycling options will be increased and the impact of global climatic change is likely to be reduced. Though governmental policies to promote recycling can be seen all around the globe, they still need to be improved so that every individual contributes. As far as Mainland China and Hong Kong are concerned, recycling systems can be seen in major areas, photos taken in Mainland China (Shenzhen) and Hong Kong (Hung Hom) are presented in Figs. 8-16 and 8-17. Also in order to support government's activities, individuals also need to take the initiatives to promote recycling activities. One typical example is the initiative taken by residents of an apartment block in Hong Kong to promote recycling options, which can be seen from Figs. 8-18 and 8-19. Such activities should be initiated and continued by all individuals.

The emphasis of the interpretation phase of this analysis is not on concluding which bag is better, but rather on how to reduce the environmental impacts caused by any shopping bags. One of the possible ways to decipher this is by means of finding ways to reduce, reuse and recycle. In fact, many retail stores have started implementing this philosophy by reducing, recycling and reusing the grocery bags. Building up public awareness and motivation to reduce, reuse and recycle all these bags will help to resolve the environmental problems to a greater extent.

Figure 8-16 Recycling system in Mainland China (Shenzhen City)

Figure 8-17 Recycling system in Hong Kong (Hung Hom Area)

Figure 8-18 Recycling bins from an apartment in HK

Figure 8-19 Recycling bins for used clothes recycling from an apartment in HK

8.6 Conclusions

This chapter reports the eco-functional assessments carried out in two areas. The first area is the assessment of any textile product/shopping bag in terms of its eco-functional aspect and the method of deriving eco-functional index/score of any textile product/shopping bag. From the eco-functional assessment model developed in this study, none of the shopping bags of this study were able to meet the requirements of eco-functional assessment. The second area is the testing of four research questions formed in Chapter 3 by conducting an eco-functional assessment combined with life cycle assessment (LCA) to assess the carbon footprint, eco-damage and ecological footprint of the different life cycle phases of various shopping bags with the aid of SIMAPRO version 7.3 of LCA software. From the LCA results, it was understood that PP bags assume the first position in terms of making the smallest impacts followed by PET and cotton bags. Impacts of LDPE bags seem to be the highest compared to their counterparts. Also, each phase of life cycle impacted the final results. The consumption process, influenced by the functionality considerations of a bag is supposed to be the most preferred option to reduce the overall life cycle impacts of various shopping bags.

Chapter 9 Conclusions and Directions for Further Research

9.1. Conclusions

This study introduced the concept of eco-functionality (interrelation and interaction among functional, ecological and consumer behaviour factors) and verified the applications with regard to various shopping bags used for grocery purposes. As explained in Chapter 2, knowledge gaps pertaining to the concept of eco-functional textiles and specific to shopping bags were identified and the proposed objectives were explored systematically and achieved satisfactorily. The theoretical framework for "eco-functional textiles" was proposed with various relevant inputs and outputs. These inputs and outputs and their interrelation can provide a profile of the essential characteristics for eco-functional assessment of any textile product or any shopping bag. An eco-functional model was developed to assess the various shopping bags/textile products in terms of eco-functional considerations involving different rules, standards, formulae and sub-models. 23 samples made out of different types of shopping bags were assessed in terms of their eco-functional properties and the eco-functional score of each bag was evaluated and the results were presented.

This study also attempted to conduct an eco-functional assessment combined with the life cycle assessment study of various shopping bags, studying the interrelation of functional, ecological and consumption process. The carbon, ecological footprints and eco-damage caused by various shopping bags were assessed with the aid of SIMAPRO version 7.3 and the degree of influence of each phase of life cycle on the final impact results was studied by means of four research questions. A suitable functional unit based on consumption statistics from Mainland China, Hong Kong and India was earmarked for this comprehensive LCA study.

For the raw material stage, a model was created to evaluate and quantify the environmental impact index (EI) and ecological sustainability index (ESI) of different textile fibres and other raw materials used for shopping bags. From the developed model, it was found that organic cotton is the most and acrylic the least sustainable fibre.

As far as process of manufacture is concerned, this research demonstrated an approach to conducting a life cycle audit in a factory that manufactures a range of nonwoven shopping bags to obtain the primary data for the production processes of different types of nonwoven bags. Life cycle impacts of manufacturing phase of various shopping bags were quantified by characterizing and normalizing the impacts pertaining to consumers in Mainland China. The manual calculation results were verified with the commercial software, SIMAPRO version 7.2.

To date, the end-of-life scenarios in the life cycle assessment of shopping bags have been largely assumed, but this rarely reflects reality with any accuracy. This study has attempted to model the end-of-life scenarios from the values obtained from the users of shopping bags, administered through a questionnaire survey study conducted among different user groups in Mainland China, Hong Kong and India.

For functional properties, a comprehensive list was drawn up and evaluated in this study. Since no instruments that are able to quantify the eco-functional properties of shopping bags (reusability, impact strength and weight-holding capacity) have been reported in the literature to date, this study has developed a new instrument to evaluate the eco-functional properties. From the experimentation results, it is clear that the reusable bags made out of cotton exhibited better results in terms of the eco-functional properties. Experimental results from the eco-functional tester along with other functional results were utilised to re-examine consumers' perceptions of end-of-life scenario values. The eco-functional assessment study combined with the LCA study was remodelled and the results were reported accordingly.

Biodegradability of various shopping bags was tested on the same platform using the soil burial test. Soil burial test results showed that paper bags followed by cotton bags demonstrated better biodegradation results. An attempt was made in this research to develop a model to quantify the recyclability potential index (RPI) of various textile fibres and raw materials used for shopping bags. Results of RPI model indicate that polypropylene and polyester outscored all the other materials in question. Results of RPI model and the biodegradability test were employed to re-examine the end-of-life values of consumers' perceptions and the LCA study was remodelled and the results were reported accordingly. A consolidated picture of the significance and originality of this research work is illustrated in Fig. 9-1 to highlight the original contributions.

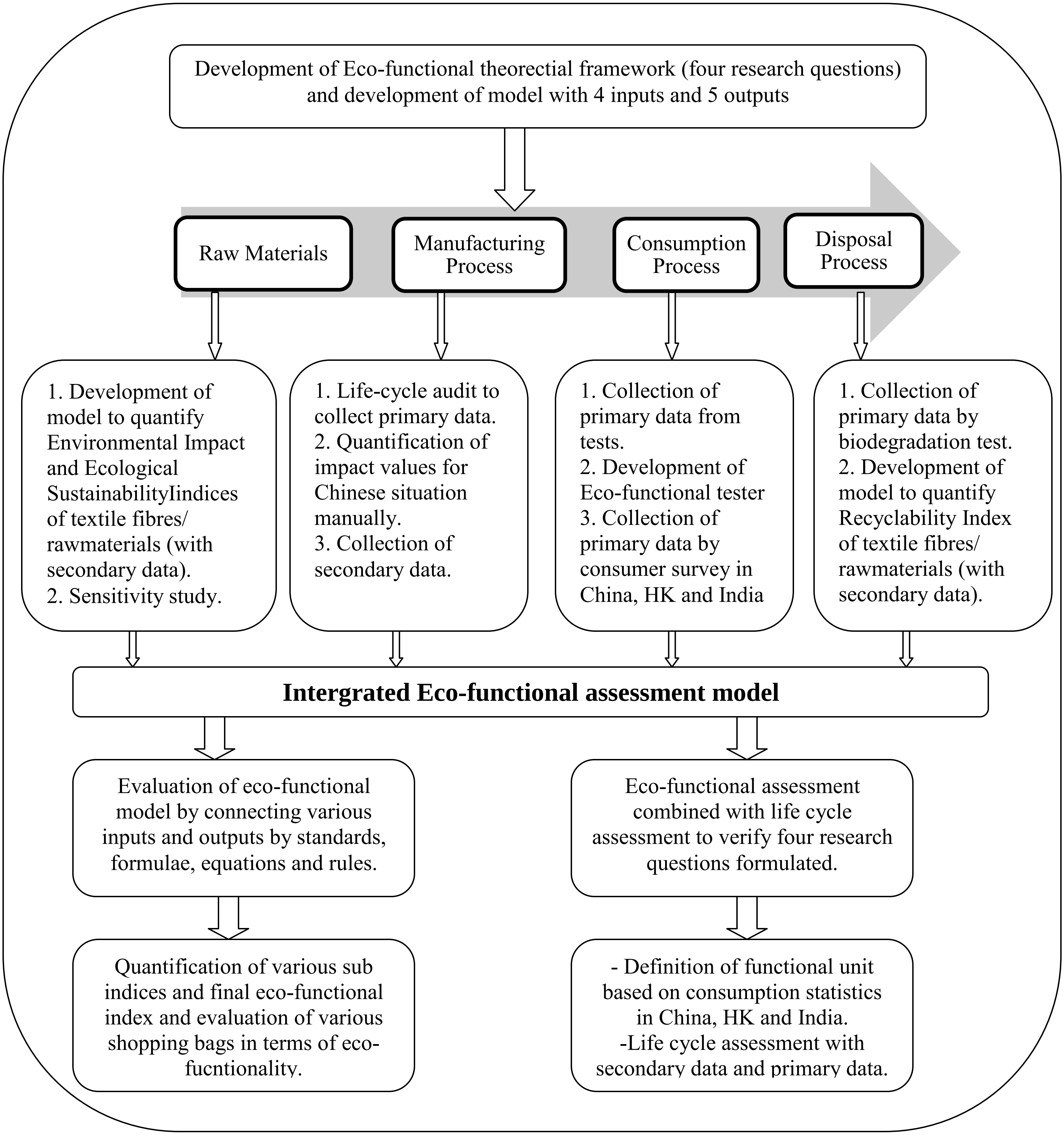


Figure 9-1 Significance and originality of the research work

From the results of the eco-functional assessments, it can be seen that none of the bags under question were able to meet the requirements of eco-functionality stipulated in this study. These results reveal the importance of every aspect of a product meeting the requirements of eco-functional assessment. From the results of the eco-functional assessment combined with the LCA study, it was noted that the carbon, ecological footprints and eco-damage created by an average Indian were lower than an average Chinese and HK resident. Reusable bags made out of PP seems to the best option in terms of the lowest life cycle impacts created followed by PET, woven , HDPE, paper and LDPE bags. Reusable bags outscore single use bags. It was also verified that each phase in the life cycle impacted the final results.

Reducing the environmental impacts of shopping bags to a greater extent lies in the hands of consumers. Reusing a bag for its primary purpose till its end-of-life and reusing it for secondary purposes afterwards will curtail environmental impacts dramatically. The next best destination for the bags is recycling followed by disposal to landfill. Hence, consumer behaviour, supplemented by the functional and ecological properties of shopping bags, is the key to reduce the environmental impacts of shopping bags.

It is the major responsibility of consumers to reuse a shopping bag as many times as possible till it is discarded. The liability of manufacturers lies in selecting an environmentally friendly raw material or low eco-impact raw material and to select a manufacturing process which consumes the least possible energy and emits few GHGs. It is also vital to provide the required functionality in a shopping bag to the maximum possible extent. For instance, in light of the results of this study, if a manufacturer wants to make a nonwoven bag, he can choose PET instead of PP and can use sewing technology (to gain better functionality) rather than the thermal technology discussed in this study.

In this study, the concept of the EI, ESI and RPI of fibres, derivation of eco-functional index, criteria for assessment of pass/fail of product in terms of eco-functional considerations were assessed with a subjective ranking system. This is a limitation of the study, but will be overcome in the near future by the scores being mutually agreed by industrial partners, standards committees and so on. The acknowledged limitations of the models can largely be offset against their flexibility in terms of providing a basis for negotiation among partners and the potential for differential weighting of various factors.

9.2. Directions for further research

The directions for further research include expanding the eco-functional assessment interface into a website, which will be publicly available for verification of products. A huge database should be compiled for a range of textile products and also other shopping bags in terms of their functional properties, ecological properties and life cycle inventory details for the various life cycle phases. At present, such a resource is not available. In future, the concept of eco-functionality can be verified with various apparels for different applications made out of different fibres. It would be very interesting to study the influence of functional, ecological and consumption processes of apparels used for various applications, including significant single use products such as diapers.

Appendices

Appendix-1

Life cycle audit – Audit Report- Observations

Action Nonwovens Company Limited, Shenzhen

Factory Visit -Observations Report for Life Cycle Assessment of Shopping Bags

Visited By:

Muthu Subramanian Senthilkannan & Xiao Liao.

Date: 7-11 December 2009.

Factory visit schedule in Shenzhen, Mainland China

(7 Dec. to 11 Dec., 2009)

Polyu members: Muthu Subramanian SenthilKannan (7-11th Dec 2009)
LIAO Xiao;

Factory manager: Mr. Thomas Wong : 9209 7228 / 13802232515

	7 Dec. Mon	8 Dec. Tue	9 Dec. Wed	10 Dec. Thu	11 Dec. Fri
Am	-	-Discuss the overall visit schedule & sample request	-Review Process B: Spun-bonding	Review-Process C: Cutting	-Review Process E: Sewing & Process F: Packaging
Pm	-Arrive -Pack down -Overall visit the factory	-Review Process A: Polypropylene Chips Manufacture	-Half Revision -Check data collected -By Kannan ONLY	Review-Process D: Screen Printing	-Review the visit with data -Pack up

Action Nonwovens Co. ltd, Shenzhen.
Visit: 7-11 Dec, 2009.

General Introduction:

Their process starts from procurement of PP and Master Batch from outside and they manufacture spun bind fabrics in one factory of them and they send the produced spun bonded fabrics to other factory of them, where cutting, screen printing, sewing and final packing of shopping bags take place. This study mainly focuses on considering the environmental inputs and outputs of shopping bags manufacturing process from this factory.

PP Chips:

- Procure from many manufacturers, very important suppliers from which they procure PP chips for shopping bags are:
    1. LG from Korea – H 7700
    2. Exxon Mobil, USA from Singapore – PP 3155E3
    3. Dalim from Korea – HP 563 S
    4. Borolis from North Europe

- Exxon Mobil from Singapore: Transportation details: USA - Singapore to Shenzhen by sea freight; Shenzhen port – Factory: about 60 KMS by Truck.
- Physical Properties: Material Flow Rate – 31-42 g/10 mins; Yellowness Index, Water Content depends on the content.
- PP 3155 E3: MFR – 36 g/10 min; Density – 0.9 g/cm3; Tenacity@break – 2.6 GPD; Elongation@ break -165%

Master Batch:

- Procured from outside.

- Hd- colour.com.
- Diameter: 100% located in 3-4 mm.
- Water Content: < 0.3%

Spun Bonding:

- Three lines of spun bonding.
- Shopping bags are manufactured from Lines 2 and 3.
- Materials needed for the production of spunbond fabrics:
    1. PP chips
    2. Master Batch
    3. Paper Tubes
    4. Tape
    5. Plastic sheets – PE
    6. Water and Naoh for cleaning.
    7. Electricity as power input.

- Outputs:
    1. Spunbond fabrics
    2. Waste fabrics being sold (Low quality).
    3. Fabrics from multi colour and being sold.
    4. Solid waste being recycled.

5. Emissions – Water and Air.

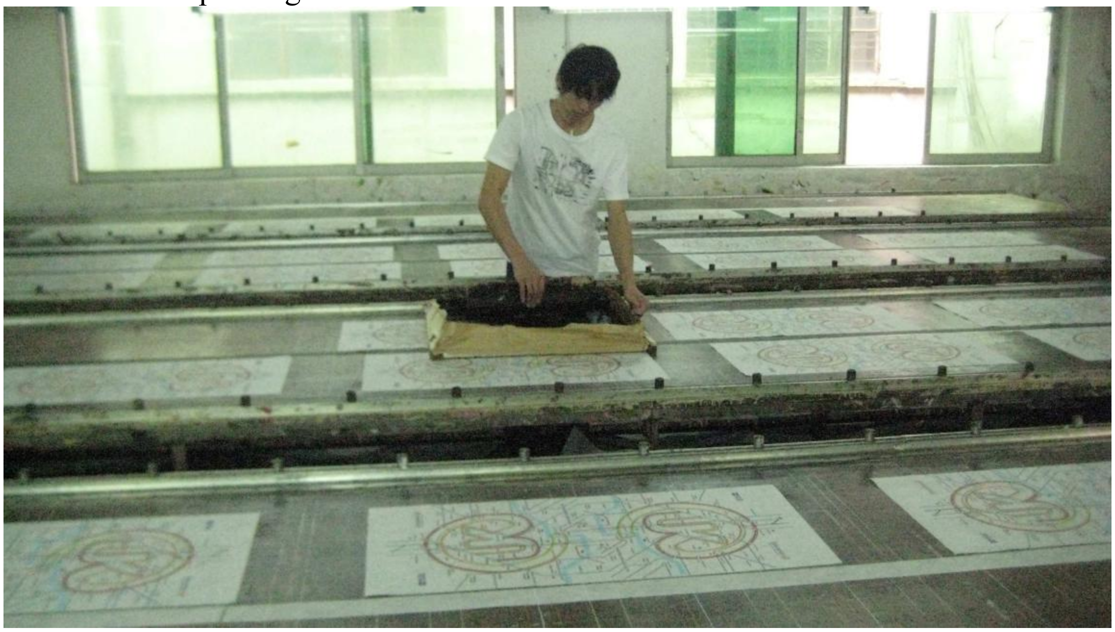
Spreading & Cutting:

- Transportation from spunbond factory – 6 km by truck (5T/3T); Code 0 Gas operated; 1 lot will carry an approximate of 30 rolls.
- Manual Spreading.
- Negligible chemical of silicone spray cote used.
- Cutting Table details: 3.5 m Width and 15.8 m length.
- Waste goes to recycling factory.
- Only electricity is used to generate power for fans and lighting,
- No additions to cutting process.
- Emissions – Nil.
- Maintenance for cutting machine: every 2 months..No cleaning..just check for proper functioning.
- Two Cutters used and one pattern cutting machine
- No preprocessing, directly process fabric rolls.
- 1 Roll of fabric: 3.2m width, 75 GSM, Length- 400 meters; for 100 GSM – 300 metres.
- Input:
    1. Fabrics
    2. Electricity
- Chemical used for cutters

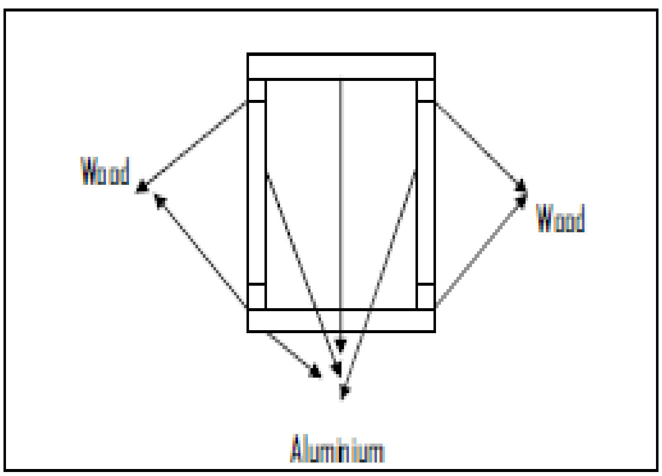
- Output:
    1. Solid waste, recycled by spun bonding
    2. Cut Fabrics

Screen-printing:

- Manual screen printing.



- 6 screen printing tables.
- Use Polyester mesh fabrics screen and aluminium and wood frame screens.
- PE films are used to transfer the document.
- PE films are being sold after use.
- Lighting and fans.
- ASB - Cyanoacrylate is used for bonding.- 20 packets/month.



Screen used for Screen printing

- Ingredients:
    - ◆ Cyclohexanone
    - ◆ DJW – 001 X – dry spot lifter.
    - ◆ ASB – Cyanoacrylate
    - ◆ Autotype Plus 7000 direct emulsion for PE films.(0.25 litre for 1 screen of 30*30 cms)
    - ◆ Hardener emulsion from Murakami – 1 Kg for 400-500 screens.

- ◆ Adhesive to stick screens.
- Maintenance: once in 6 months; 6 tables need 75 kgs/wash/6 months.
- Inputs: Screen and its ingredients; Cut fabric;
- Outputs: Screen printed fabric.
- Manual transport and sometimes lift is used to transport.

Sewing:

- Two types of sewing – by thermal means and by thread sewing.
- Manual transport and sometimes lift is used to transport.
- PET/Nylon threads are used.
- Inputs for Thread sewing: Threads (PET – 100%) and screen printed fabrics, electricity for machine operation.
- Outputs: Sewn Shopping bag attached with handles.
- Inputs for thermal attachment: Screen printed fabrics (Cut/uncut), electricity for thermal power and air pressure.
- Outputs: Shopping bag with handles.

Packaging:
- Manual packaging.
- Use paper cartons – 1 for 100 bags. (40*40*30 cm)
- PE sheets – 1 for 50 Pcs.

Overall Observations and recommendations:
- *Generally, good measures of recycling are happening all around the factory. For example, recycling the solid waste of spun bond production and waste in cutting factory are being recycled to PP chips successfully, which is really a promising*

measure for future. The same way, certain amount of cutting waste is being reused as shopping bag handles. So, environmental impact wise, it is better and beneficial in cost wise too.

- Also certain wastes are being sold as seconds rather than throwing it to landfill.

- In Spun bond factory, water used for cooling is being recycled by recooling and reused again.

- In Spun bond and cutting factory, still inventory management is not up to the mark, which is a major pitfall of this factory. Inventory details for each sort are very difficult to get in the current system and it is mandatory for this factory to improve upon this, especially while producing multi products.

- Also, difficult to calculate solid waste in the factories. Quantification of this is very much pivotal.

- Overall the factory is going in a proper direction as far as environmental measures are concerned. If they improve the inventory system, they can kiss greater heights.

Appendix-2

LCA manual calculations

Emission Inventory for electricity in China	Kg/kWh	g/kWh
Consumption of coal	4.57E-01	4.57E+02
Consumption of oil	8.80E-03	8.80E+00
Consumption of gas	7.95E-03	7.95E+00
Consumption of enriched uranium	9.03E-08	9.03E-05
CO_2	8.77E-01	8.77E+02
SO_2	8.04E-03	8.04E+00
NO_x	5.23E-03	5.23E+00
CO	1.25E-03	1.25E+00
CH_4	2.65E-03	2.65E+00
Nonmethane volatile organic compound (NMVOC)	3.95E-04	3.95E-01
Dust	1.63E-02	1.63E+01
As	1.62E-06	1.62E-03
Cd	1.03E-08	1.03E-05
Cr	1.37E-07	1.37E-04
Hg	7.11E-08	7.11E-05
Ni	2.03E-07	2.03E-04
Pb	1.42E-06	1.42E-03
V	2.33E-06	2.33E-03
Zn	1.94E-06	1.94E-03
Emissions of waste water	1.31E+00	1.31E+03
COD	6.02E-05	6.02E-02
Coal fly ash	8.34E-02	8.34E+01
Slag	1.87E-02	1.87E+01
Halogen in Bq	3.74E+01	3.74E+04
Gasoloid in Bq	1.61E-01	1.61E+02
Tritium in Bq	4.22E+01	4.22E+04
Non-tritium in Bq	4.06E-02	4.06E+01
Radioactive solid waste in m^3	2.68E-10	2.68E-07

Table 1 Electricity inventory for China

Emission Inventory for electricity in china	g/kWh	Plastic bag (HDPE) 0.11 Kwh	Paper bag (Kraft paper) 0.39 Kwh	PP fibre nonwoven bag 3.1 Kwh	Woven cotton Bag 4.88 Kwh	Boutique plastic (LDPE) 0.41 Kwh
Consumption of coal	4.57E+02	5.03E+01	1.78E+02	1.42E+03	2.23E+03	1.87E+02
Consumption of oil	8.80E+00	9.68E-01	3.43E+00	2.73E+01	4.29E+01	3.61E+00
Consumption of gas	7.95E+00	8.75E-01	3.10E+00	2.46E+01	3.88E+01	3.26E+00
Consumption of enriched uranium	9.03E-05	9.93E-06	3.52E-05	2.80E-04	4.41E-04	3.70E-05
CO_2	8.77E+02	9.65E+01	3.42E+02	2.72E+03	4.28E+03	3.60E+02
SO_2	8.04E+00	8.84E-01	3.14E+00	2.49E+01	3.92E+01	3.30E+00
NO_x	5.23E+00	5.75E-01	2.04E+00	1.62E+01	2.55E+01	2.14E+00
CO	1.25E+00	1.38E-01	4.88E-01	3.88E+00	6.10E+00	5.13E-01
CH_4	2.65E+00	2.92E-01	1.03E+00	8.22E+00	1.29E+01	1.09E+00
NMVOC	3.95E-01	4.35E-02	1.54E-01	1.22E+00	1.93E+00	1.62E-01
Dust	1.63E+01	1.79E+00	6.36E+00	5.05E+01	7.95E+01	6.68E+00
As	1.62E-03	1.78E-04	6.32E-04	5.02E-03	7.91E-03	6.64E-04
Cd	1.03E-05	1.13E-06	4.02E-06	3.19E-05	5.03E-05	4.22E-06
Cr	1.37E-04	1.51E-05	5.34E-05	4.25E-04	6.69E-04	5.62E-05
Hg	7.11E-05	7.82E-06	2.77E-05	2.20E-04	3.47E-04	2.92E-05
Ni	2.03E-04	2.23E-05	7.92E-05	6.29E-04	9.91E-04	8.32E-05
Pb	1.42E-03	1.56E-04	5.54E-04	4.40E-03	6.93E-03	5.82E-04
V	2.33E-03	2.56E-04	9.09E-04	7.22E-03	1.14E-02	9.55E-04
Zn	1.94E-03	2.13E-04	7.57E-04	6.01E-03	9.47E-03	7.95E-04
Emissions of waste water	1.31E+03	1.44E+02	5.11E+02	4.06E+03	6.39E+03	5.37E+02

COD	6.02E-02	6.62E-03	2.35E-02	1.87E-01	2.94E-01	2.47E-02
Coal fly ash	8.34E+01	9.17E+00	3.25E+01	2.59E+02	4.07E+02	3.42E+01
Slag	1.87E+01	2.06E+00	7.29E+00	5.80E+01	9.13E+01	7.67E+00
Halogen in Bq	3.74E+04	4.11E+03	1.46E+04	1.16E+05	1.83E+05	1.53E+04
Gasoloid in Bq	1.61E+02	1.77E+01	6.28E+01	4.99E+02	7.86E+02	6.60E+01
Tritium in Bq	4.22E+04	4.64E+03	1.65E+04	1.31E+05	2.06E+05	1.73E+04
Non-tritium in Bq	4.06E+01	4.47E+00	1.58E+01	1.26E+02	1.98E+02	1.66E+01
Radioactive solid waste in m^3	2.68E-07	2.95E-08	1.05E-07	8.31E-07	1.31E-06	1.10E-07

Table 2 Emission Inventory for Shopping Bags for Electricity input per bag

Inventory	Plastic bag (HDPE)	Paper bag (Kraft paper)	PP fibre nonwoven bag	Woven cotton Bag	Boutique plastic (LDPE)
Consumption of coal	5.03E-02	1.78E-01	1.42E+00	2.23E+00	1.87E-01
Consumption of oil	9.68E-04	3.43E-03	2.73E-02	4.29E-02	3.61E-03
Consumption of gas	8.75E-04	3.10E-03	2.46E-02	3.88E-02	3.26E-02
Consumption of enriched uranium	9.93E-09	3.52E-08	2.80E-07	4.41E-07	3.70E-08
CO_2	1.08E-01	3.65E-01	3.19E+00	4.56E+00	4.05E-01
SO_2	8.84E-04	3.14E-03	2.49E-02	3.92E-02	3.30E-03
NO_x	5.75E-04	2.04E-03	1.62E-02	2.55E-02	2.14E-03
CO	1.38E-04	4.88E-04	3.88E-03	6.10E-03	5.13E-04
CH_4	2.92E-04	1.03E-03	8.22E-03	1.29E-02	1.09E-03
Nonmethane volatile organic compound (NMVOC)	4.35E-05	1.54E-04	1.22E-03	1.93E-03	1.62E-04
Dust	1.79E-03	6.36E-03	5.05E-02	7.95E-02	6.68E-03
As	1.78E-07	6.32E-07	5.02E-06	7.91E-06	6.64E-07
Cd	1.13E-09	4.02E-09	3.19E-08	5.03E-08	4.22E-09
Cr	1.51E-08	5.34E-08	4.25E-07	6.69E-07	5.62E-08
Hg	7.82E-09	2.77E-08	2.20E-07	3.47E-07	2.92E-08
Ni	2.23E-08	7.92E-08	6.29E-07	9.91E-07	8.32E-08
Pb	1.56E-07	5.54E-07	4.40E-06	6.93E-06	5.82E-07
V	2.56E-07	9.09E-07	7.22E-06	1.14E-05	9.55E-07
Zn	2.13E-07	7.57E-07	6.01E-06	9.47E-06	7.95E-07

Emissions of waste water	1.44E-01	5.11E-01	4.06E+00	6.39E+00	5.37E-01
COD	6.62E-06	2.35E-05	1.87E-04	2.94E-04	2.47E-05
Coal fly ash	9.17E-03	3.25E-02	2.59E-01	4.07E-01	3.42E-02
Slag	2.06E-03	7.29E-03	5.80E-02	9.13E-02	7.67E-03
Halogen in Bq	4.11E+00	1.46E+01	1.16E+02	1.83E+02	1.53E+01
Gasoloid in Bq	1.77E-02	6.28E-02	4.99E-01	7.86E-01	6.60E-02
Tritium in Bq	4.64E+00	1.65E+01	1.31E+02	2.06E+02	1.73E+01
Non-tritium in Bq	4.47E-03	1.58E-02	1.26E-01	1.98E-01	1.66E-02
Radioactive solid waste in m^3	2.95E-11	1.05E-10	8.31E-10	1.31E-09	1.10E-10

Table 3 Total inventory for production processes of shopping bags per bag in Kilograms

Inventory	ELU for natural resources (ELU/Kg)	ELU for emissions-Air (ELU/Kg)	ELU for emissions-Fresh Water(ELU/Kg)	ELU for emissions-Sea Water (ELU/Kg)	ADP (in kg antimony eq./kg)
Coal	5.00E-02				0.0134 (hard coal)
Oil	5.00E-01				2.01E-02
Gas	1.1 [100]				0.0187 (natural gas) (kg antimony/m^3 natural gas)
Uranium	1.26E+03				2.87E-03
CO_2		6.36E-02			
SO_2		5.45E-02			

NO_x		3.95E-01			
CO		1.91E-01			
CH_4		1.56E+00			
NMVOC					
Dust		0.0071 (PM_{10})			
As	1.90E+03	1.00E+01			9.17E-03
Cd	2.30E+04	2.12E+01			3.30E-01
Cr	3.30E+01	8.00E-01			8.58E-04
Hg	4.00E+04	1.77E+02			4.95E-01
Ni	4.00E+01				1.08E-04
Pb	2.40E+02	2.91E+02			1.35E-02
V	2.83E+01				1.16E-06
Zn	4.90E+01				9.92E-04
waste water					
COD			6.00E-03		
Coal fly ash					
Slag					
Halogen fluorine (F), chlorine (Cl), bromine (Br), iodine (I), and astatine (At)					
Gasoloid					
Tritium					
Non-tritium					
Radioactive solid waste					

Table 4 Environmental Burden- ELU & Depletion of Abiotic Resources

Inventory	ADP (in kg antimony eq./kg)	Reserve Kg	Normalisation Figures
Coal	7.97×10^{-8}	5.86×10^{7}	2.14E-03
Oil	9.91×10^{-5}	8.74×10^{8}	1.15E-07
Gas	8.89×10^{-8}	3.85×10^{8}	2.92E-04
Cr	6.31×10^{-2}	6.17×10^{8}	2.57E-10
Hg	7.46E+00	5.97×10^{8}	2.25E-11
Ni	5.65×10^{-2}	4.21×10^{8}	4.20E-10
Pb	4.36×10^{-2}	1.64×10^{9}	1.40E-10
Zn	1.16×10^{-2}	1.12×10^{9}	7.70E-10
Total			2.43E-03
			4.67×10−11

Table 5 Chinese Characterisation and Normalization factors for ADP

Inventory	Climate Change (GWP_{100}) (Air)	Ozone Depletion (ODP)	HTP -100 yr (Kg 1,4-DCB eq./kg) Air	HTP -100 yr (Kg 1,4-DCB eq./kg) Fresh Water	HTP -100 yr (Kg 1,4-DCB eq./kg) Sea Water	HTP -100 yr (Kg 1,4-DCB eq./kg) Agri Soil	HTP -100 yr (Kg 1,4-DCB eq./kg) Industrial Soil
Coal							
Oil							
Gas							
Uranium							
CO_2	1						
SO_2			9.6E-02	X	X	X	X
NO_x			1.2E+00	X	X	X	X
CO							
CH_4	21						
NMVOC Benzene/1,1,1-trichloroethane	/110	/0.11	1.9E+03/ 1.6E+01	1.8E+03/ 1.6E+01	2.1E +02/ 9.6E+00	1.5 E+04/ 1.6 E+01	1.6E+03/ 1.6E+01
Dust			8.2E-01	X	X	X	X
As			3.5E+05	1.3E+02	3.1E+01	3.1E+02	4.8E+00
Cd			1.5E+05	1.1E+01	6.9E+00	2.8E+03	8.7E+00
Cr							
Hg - Mercury			2.6E+02	1.0E+02	1.2E+02	1.3E+02	9.5E+00

Ni			3.5E+04	4.3E+01	7.8E+00	1.7E+02	3.0E+00
Pb -Lead			2.9E+01	5.2E+00	7.1E+00	2.7E+01	2.4E+00
V			2.6E+02	2.7E+02	4.6E+01	1.3E+03	1.4E+01
Zn			9.6E+01	2. E-01	2.0E-01	4.5E+00	1.5E-02
waste water							
COD							
Coal fly ash							
Slag							
Halogen fluorine (F), chlorine (Cl), bromine (Br), iodine (I), and astatine (At)							
Gasoloid							
Tritium							
Non-tritium							
Radioactive solid waste							

Table 6 Characterisation values for GWP, ODP and Human Toxicity

Inventory	Acidification potential (in Kg SO_2-eq./kg)	Eutrophication potential (in Kg PO_4^{3-}-eq./kg)	Ionising Radiation – Damage Factor ($Yr.KBq^{-1}$) in Air	Ionising Radiation – Damage Factor ($Yr.KBq^{-1}$) in Sea Water	POCP (in kg ethylene eq./kg)
Coal					
Oil					
Gas					
Uranium					

CO_2					
SO_2	1.00E+00				4.80E-02
NO_x	7.00E-01	1.30E-01			2.80E-02
CO					2.70E-02
CH_4					6.00E-03
NMVOC Benzene/1,1,1-trichloroethane					0.218/ 0.009
Dust					
As					
Cd					
Cr					
Hg - Mercury					
Ni					
Pb -Lead					
V					
Zn					
waste water					
COD		2.20E-02			
Coal fly ash					
Slag					
Halogen fluorine (F), chlorine (Cl), bromine (Br), iodine (I), and astatine (At)					
Gasoloid					
Tritium			1.40E-11	6.9E-14	

Non-tritium					
Radioactive solid waste					

Table 7 Characterisation values for Acidification, Eutrophication, Radiation & POCP

Inventory	Plastic bag (HDPE)	Paper bag (Kraft paper)	PP fibre nonwoven bag	Woven cotton Bag	Boutique plastic (LDPE)
Consumption of coal	2.11E-02	7.49E-02	5.95E-01	9.37E-01	7.87E-02
Consumption of oil	4.84E-04	1.72E-03	1.36E-02	2.15E-02	1.80E-03
Consumption of gas	9.62E-04	3.41E-03	2.71E-02	4.27E-02	3.59E-02
Consumption of enriched uranium	1.25E-05	4.44E-05	3.53E-04	5.56E-04	4.66E-05
CO_2					
SO_2					
NO_x					
CO					
CH_4					
Nonmethane volatile organic compound (NMVOC)					
Dust					
As	3.40E-04	1.20E-03	9.54E-03	1.50E-02	1.26E-03
Cd	2.60E-05	9.25E-05	7.34E-04	1.16E-03	9.71E-05
Cr	4.98E-07	1.76E-06	1.40E-05	2.21E-05	1.86E-05
Hg	3.13E-04	1.11E-03	8.80E-03	1.39E-02	1.17E-03
Ni	8.92E-07	3.17E-06	2.52E-05	3.96E-05	3.33E-06

Pb	3.74E-05	1.33E-04	1.06E-03	1.66E-03	1.40E-04
V	7.25E-06	2.57E-05	2.04E-04	3.22E-04	2.70E-05
Zn	1.04E-05	3.71E-05	2.95E-04	4.64E-04	3.90E-05
Emissions of waste water					
COD					
Coal fly ash					
Slag					
Halogen					
Gasoloid					
Tritium					
Non-tritium					
Radioactive solid waste					
Total	4.71E-03	1.67E-02	1.33E-01	2.09E-01	4.98E-02

Table 8 ELU – Natural Resources

Inventory	Plastic bag (HDPE)	Paper bag (Kraft paper)	PP fibre nonwoven bag	Woven cotton Bag	Boutique plastic (LDPE)
Consumption of coal					
Consumption of oil					
Consumption of gas					

Consumption of enriched uranium					
CO_2	6.87E-03	2.32E-02	2.03E-01	2.90E-01	2.58E-02
SO_2	4.82E-05	1.71E-04	1.36E-03	2.14E-03	1.80E-04
NO_x	2.27E-04	8.06E-04	6.40E-03	1.01E-02	8.47E-04
CO	2.63E-05	9.31E-05	7.40E-04	1.17E-03	9.79E-05
CH_4	4.55E-04	1.61E-03	1.28E-02	2.02E-02	1.69E-03
Nonmethane volatile organic compound (NMVOC)					
Dust	1.27E-05	4.51E-05	3.59E-04	5.65E-04	4.74E-05
As	1.78E-06	6.32E-06	5.02E-05	7.91E-05	6.64E-06
Cd	2.40E-08	8.52E-08	6.76E-07	1.07E-06	8.95E-08
Cr	1.21E-08	4.27E-08	3.40E-07	5.35E-07	4.50E-08
Hg	1.38E-06	4.90E-06	3.89E-05	6.14E-05	5.17E-06
Ni					
Pb	4.54E-05	1.61E-04	1.28E-03	2.02E-03	1.69E-04
V					
Zn					
Emissions of waste water					
COD	3.97E-08	1.41E-07	1.12E-06	1.76E-06	1.48E-07
Coal fly ash					
Slag					
Halogen					

Gasoloid					
Tritium					
Non-tritium					
Radioactive solid waste					
Total	7.69E-03	2.61E-02	2.26E-01	3.26E-01	2.88E-02

Table 9 ELU – Emissions

Inventory	Plastic bag (HDPE)	Paper bag (Kraft paper)	PP fibre nonwoven bag	Woven cotton Bag	Boutique plastic (LDPE)
Consumption of coal	6.74E-04	2.39E-03	1.90E-02	2.99E-02	2.51E-03
Consumption of oil	1.95E-05	6.90E-05	5.48E-04	8.63E-04	7.25E-05
Consumption of gas	1.64E-05	5.80E-05	4.61E-04	7.25E-04	6.10E-04
Consumption of enriched uranium	2.85E-11	1.01E-10	8.04E-10	1.27E-09	1.06E-10
CO_2					
SO_2					
NO_x					
CO					
CH_4					
Nonmethane volatile organic compound (NMVOC)					

Dust					
As	1.63E-09	5.80E-09	4.61E-08	7.25E-08	6.09E-09
Cd	3.73E-10	1.33E-09	1.05E-08	1.66E-08	1.39E-09
Cr	1.30E-11	4.58E-11	3.65E-10	5.74E-10	4.82E-11
Hg	3.87E-09	1.37E-08	1.09E-07	1.72E-07	1.45E-08
Ni	2.41E-12	8.55E-12	6.79E-11	1.07E-10	8.99E-12
Pb	2.11E-09	7.48E-09	5.94E-08	9.36E-08	7.86E-09
V	2.97E-13	1.05E-12	8.38E-12	1.32E-11	1.11E-12
Zn	2.11E-10	7.51E-10	5.97E-09	9.39E-09	7.89E-10
Emissions of waste water					
COD					
Coal fly ash					
Slag					
Halogen					
Gasoloid					
Tritium					
Non-tritium					
Radioactive solid waste					
Total	7.10E-04	2.52E-03	2.00E-02	3.15E-02	3.19E-03

Table 10 Depletion of Abiotic Resources in kg of the reference antimony

Inventory	Plastic bag (HDPE)	Paper bag (Kraft paper)	PP fibre nonwoven bag	Woven cotton Bag	Boutique plastic (LDPE)
Consumption of coal	4.01E-08	1.42E-07	1.13E-06	1.78E-06	1.49E-07
Consumption of oil	9.59E-07	3.40E-06	2.70E-05	4.26E-05	3.58E-06
Consumption of gas	7.77E-10	2.76E-09	2.19E-08	3.45E-08	2.90E-08
Consumption of enriched uranium	9.53E-09	3.37E-08	2.68E-07	4.22E-07	3.55E-08
CO_2					
SO_2					
NO_x					
CO					
CH_4					
Nonmethane volatile organic compound (NMVOC)					
Dust					
As					
Cd					
Cr					
Hg	5.83E-08	2.07E-07	1.64E-06	2.59E-06	2.18E-07
Ni	1.26E-08	4.47E-08	3.55E-07	5.60E-07	4.70E-08
Pb	6.84E-08	2.42E-07	1.92E-06	3.02E-06	2.54E-07
V					

Zn	2.47E-08	8.78E-08	6.98E-07	1.10E-06	9.22E-08
Emissions of waste water					
COD					
Coal fly ash					
Slag					
Halogen					
Gasoloid					
Tritium					
Non-tritium					
Radioactive solid waste					
Total	1.17E-06	4.16E-06	3.24E-05	5.21E-05	4.40E-06

Table 11 Depletion of Abiotic Resources in kg of the reference antimony (Natural Resources) – Chinese Characterisation factors

Inventory	Plastic bag (HDPE)	Paper bag (Kraft paper)	PP fibre nonwoven bag	Woven cotton Bag	Boutique plastic (LDPE)
Consumption of coal					
Consumption of oil					
Consumption of gas					
Consumption of enriched					

uranium					
CO_2	1.08E-01	3.65E-01	3.19E+00	4.56E+00	4.05E-01
SO_2					
NO_x					
CO					
CH_4	6.12E-03	2.17E-02	1.73E-01	2.72E-01	2.28E-02
Nonmethane volatile organic compound (NMVOC) (1,1,1 Trichloroethane)	4.78E-03	1.69E-02	1.35E-01	2.12E-01	1.78E-02
Dust					
As					
Cd					
Cr					
Hg					
Ni					
Pb					
V					
Zn					
Emissions of waste water					
COD					
Coal fly ash					
Slag					
Halogen					
Gasoloid					

Tritium					
Non-tritium					
Radioactive solid waste					
Total – GWP	1.19E-01	4.03E-01	3.50E+00	5.04E+00	4.46E-01
ODP	4.78E-06	1.69E-05	1.35E-04	2.12E-04	1.78E-05

Table 12 GWP-100 Years & Ozone Depletion Potential

Inventory	Plastic bag (HDPE)	Paper bag (Kraft paper)	PP fibre nonwoven bag	Woven cotton Bag	Boutique plastic (LDPE)
Consumption of coal					
Consumption of oil					
Consumption of gas					
Consumption of enriched uranium					
CO_2					
SO_2	8.49E-05	3.01E-04	2.39E-03	3.77E-03	3.16E-04
NO_x	6.90E-04	2.45E-03	1.95E-02	3.06E-02	2.57E-03
CO					
CH_4					
Nonmethane volatile organic compound (NMVO	3.20E-03	1.13E-02	9.01E-02	1.42E-01	1.19E-02

C)					
Dust	1.47E-03	5.21E-03	4.14E-02	6.52E-02	5.48E-03
As	6.24E-02	2.22E-01	1.76E+00	2.77E+00	2.33E-01
Cd	1.73E-04	6.14E-04	4.88E-03	7.69E-03	6.45E-04
Cr					
Hg	4.84E-06	1.72E-05	1.36E-04	2.15E-04	1.81E-05
Ni					
Pb	7.85E-04	2.79E-03	2.22E-02	3.49E-02	2.93E-03
V	1.10E-05	3.92E-05	3.11E-04	4.90E-04	4.11E-05
Zn	4.84E-04	1.72E-03	1.37E-02	2.15E-02	1.80E-03
Emissions of waste water					
COD					
Coal fly ash					
Slag					
Halogen					
Gasoloid					
Tritium					
Non-tritium					
Radioactive solid waste					
Total	6.93E-02	2.46E-01	1.96E+00	3.08E+00	2.59E-01

Table 13 Human Toxicity

Inventory	Plastic bag (HDPE)	Paper bag (Kraft paper)	PP fibre nonwoven bag	Woven cotton Bag	Boutique plastic (LDPE)
SO_2	8.49E-05	3.01E-04	2.39E-03	3.77E-03	3.16E-04
NO_x	6.90E-04	2.45E-03	1.95E-02	3.06E-02	2.57E-03
NMVOC	6.95E-04	2.46E-03	1.96E-02	3.08E-02	2.59E-03
Dust	1.47E-03	5.21E-03	4.14E-02	6.52E-02	5.48E-03
As	6.23E-02	2.21E-01	1.76E+00	2.77E+00	2.32E-01
Cd	1.70E-04	6.03E-04	4.79E-03	7.55E-03	6.33E-04
Hg	2.03E-06	7.20E-06	5.72E-05	9.02E-05	7.59E-06
Ni	7.80E-05	2.77E-03	2.20E-02	3.47E-02	2.91E-03
Pb	4.52E-06	1.61E-05	1.28E-04	2.01E-04	1.69E-05
V	6.66E-05	2.36E-04	1.88E-03	2.96E-03	2.48E-04
Zn	2.04E-05	7.27E-05	5.77E-04	9.09E-04	7.63E-05
Total	6.56E-02	2.35E-01	1.87E+00	2.94E+00	2.47E-01

Table 14 Human Toxicity-Air

Inventory	Plastic bag (HDPE)	Paper bag (Kraft paper)	PP fibre nonwoven bag	Woven cotton Bag	Boutique plastic (LDPE)
NMVOC	6.95E-04	2.46E-03	1.96E-02	3.08E-02	2.59E-03
As	2.31E-05	8.22E-05	6.53E-04	1.03E-03	8.63E-05
Cd	1.24E-08	4.42E-08	3.51E-07	5.53E-07	4.64E-08
Hg	7.82E-07	2.77E-06	2.20E-05	3.47E-05	2.92E-06
Ni	9.58E-08	3.41E-06	2.70E-05	4.26E-05	3.58E-06
Pb	8.11E-07	2.88E-06	2.29E-05	3.60E-05	3.03E-06
V	6.91E-05	2.45E-04	1.95E-03	3.07E-03	2.58E-04
Zn	4.26E-08	1.51E-07	1.20E-06	1.89E-06	1.59E-07
Total	7.89E-04	2.80E-03	2.23E-02	3.51E-02	2.95E-03

Table 15 Human Toxicity- Fresh Water

Inventory	Plastic bag (HDPE)	Paper bag (Kraft paper)	PP fibre nonwoven bag	Woven cotton Bag	Boutique plastic (LDPE)
NMVOC	4.17E-04	1.48E-03	1.18E-02	1.85E-02	1.55E-03
As	5.52E-06	1.96E-05	1.56E-04	2.45E-04	2.06E-05
Cd	7.80E-09	2.77E-08	2.20E-07	3.47E-07	2.91E-08
Hg	9.38E-07	3.32E-06	2.64E-05	4.16E-05	3.50E-06
Ni	1.74E-08	6.18E-07	4.91E-06	7.73E-06	6.49E-07

Pb	1.11E-06	3.93E-06	3.13E-05	4.92E-05	4.13E-06
V	1.18E-05	4.18E-05	3.32E-04	5.23E-04	4.39E-05
Zn	4.26E-08	1.51E-07	1.20E-06	1.89E-06	1.59E-07
Total	4.36E-04	1.55E-03	1.23E-02	1.94E-02	1.63E-03

Table 16 Human Toxicity- Sea Water

Inventory	Plastic bag (HDPE)	Paper bag (Kraft paper)	PP fibre nonwoven bag	Woven cotton Bag	Boutique plastic (LDPE)
NMVOC	6.95E-04	2.46E-03	1.96E-02	3.08E-02	2.59E-03
As	5.52E-05	1.96E-04	1.56E-03	2.45E-03	2.06E-04
Cd	3.16E-06	1.13E-05	8.93E-05	1.41E-04	1.18E-05
Hg	1.02E-06	3.60E-06	2.86E-05	4.51E-05	3.80E-06
Ni	3.79E-07	1.35E-05	1.07E-04	1.68E-04	1.41E-05
Pb	4.21E-06	1.50E-05	1.19E-04	1.87E-04	1.57E-05
V	3.33E-04	1.18E-03	9.39E-03	1.48E-02	1.24E-03
Zn	9.59E-07	7.27E-05	2.71E-05	4.26E-05	3.58E-06
Total	1.09E-03	3.96E-03	3.09E-02	4.87E-02	4.09E-03

Table 17 Human Toxicity- Agricultural Soil

Inventory	Plastic bag (HDPE)	Paper bag (Kraft paper)	PP fibre nonwoven bag	Woven cotton Bag	Boutique plastic (LDPE)
NMVOC	6.95E-04	2.46E-03	1.96E-02	3.08E-02	2.59E-03
As	8.54E-07	3.03E-06	2.41E-05	3.79E-05	3.19E-06
Cd	9.83E-09	3.50E-08	2.78E-07	4.38E-07	3.67E-08
Hg	7.43E-08	2.63E-07	2.09E-06	3.30E-06	2.77E-07
Ni	6.68E-09	2.38E-07	1.89E-06	2.97E-06	2.50E-07
Pb	3.74E-07	1.33E-06	1.06E-05	1.66E-05	1.40E-06
V	3.58E-06	1.27E-05	1.01E-04	1.59E-04	1.34E-05
Zn	3.20E-09	1.14E-08	9.02E-08	1.42E-07	1.19E-08
Total	7.00E-04	2.48E-03	1.97E-02	3.11E-02	2.61E-03

Table 18 Human Toxicity- Industrial Soil

Inventory	Plastic bag (HDPE)	Paper bag (Kraft paper)	PP fibre nonwoven bag	Woven cotton Bag	Boutique plastic (LDPE)
Air	6.56E-02	2.35E-01	1.87E+00	2.94E+00	2.47E-01

Fresh Water	7.89E-04	2.80E-03	2.23E-02	3.51E-02	2.95E-03
Sea Water	4.36E-04	3.93E-06	1.23E-02	1.94E-02	1.63E-03
Agri Soil	1.09E-03	3.96E-03	3.09E-02	4.87E-02	4.09E-03
Industrial Soil	7.00E-04	2.48E-03	1.97E-02	3.11E-02	2.61E-03
Total	6.86E-02	2.45E-01	1.96E+00	3.08E+00	2.59E-01

Table 19 Human Toxicity- Total

Inventory	Plastic bag (HDPE)	Paper bag (Kraft paper)	PP fibre nonwoven bag	Woven cotton Bag	Boutique plastic (LDPE)
Consumption of coal					
Consumption of oil					
Consumption of gas					
Consumption of enriched uranium					
CO_2					
SO_2 AP	8.84E-04	3.14E-03	2.49E-02	3.92E-02	3.30E-03
SO_2 POCP	4.25E-05	1.51E-04	1.20E-03	1.88E-03	1.58E-04
NO_x AP	4.03E-04	1.43E-03	1.13E-02	1.79E-02	1.50E-03
NO_x EP	7.48E-05	2.65E-04	2.11E-03	3.32E-03	2.79E-04
NO_x POCP	1.61E-05	5.71E-05	4.54E-04	7.15E-04	6.00E-05
CO POCP	3.71E-06	1.32E-05	1.05E-04	1.65E-04	1.38E-05

CH_4 POCP	1.75E-06	6.20E-06	4.93E-05	7.76E-05	6.52E-06
Nonmethane volatile organic compound (NMVOC) POCP	3.91E-07	1.39E-06	1.10E-05	1.73E-05	1.46E-06
Dust					
As					
Cd					
Cr					
Hg					
Ni					
Pb					
V					
Zn					
Emissions of waste water					
COD-EP	1.46E-07	5.17E-07	4.11E-06	6.70E-06	5.43E-07
Coal fly ash					
Slag					
Halogen					
Gasoloid					
Tritium-Air	6.50E-11	2.30E-10	1.83E-09	2.88E-09	2.42E-10
Tritium-Sea Water	3.20E-13	1.14E-12	9.03E-12	1.42E-11	1.19E-12
Radioactive solid waste					

Total-AP	1.28E-03	4.56E-03	3.63E-02	5.71E-02	4.80E-03
Total-EP	7.49E-05	2.66E-04	2.11E-03	3.32E-03	2.79E-04
Total-POCP	6.44E-05	2.28E-04	1.82E-03	2.86E-03	2.40E-04
Total-IR	6.53E-11	2.32E-10	1.84E-09	2.90E-09	2.43E-10

Table 20 Acidification, Eutrophication, POCP & Radiation

Inventory	Plastic bag (HDPE)	Paper bag (Kraft paper)	PP fibre nonwoven bag	Woven cotton Bag	Boutique plastic (LDPE)
Radioactive solid waste in m^3	2.95E-11	1.05E-10	8.31E-10	1.31E-09	1.10E-10
Coal fly ash	9.17E-03	3.25E-02	2.59E-01	4.07E-01	3.42E-02
Slag	2.06E-03	7.29E-03	5.80E-02	9.13E-02	7.67E-03
Emissions of waste water	1.44E-01	5.11E-01	4.06E+00	6.39E+00	5.37E-01

Table 21 Other Impacts

Appendix-3

Survey Questionnaire:

Dear Reader,

We are doing a study on environmental impact of grocery shopping bags (such as those used in supermarkets and/or street markets), which becomes a critical issue. Your views are extremely important. We are very much grateful if you could contribute to this issue by answering the following questions. Please (√) tick the selected option of yours or highlight your selected option in bold letters if you want to send it back to us in electronic format. Kindly send it back to: senthilkannan@

1.	How many times do you reuse a non-plastic bag?	< 1 time	1 time	2 times	3-5 times	Others ______
2.	How many times do you reuse a paper bag?	< 1 time	1 time	2 times	3-5 times	Others ______
3.	How many times do you reuse a nonwoven (Polypropylene) shopping bag?	< 1 time	1 time	2 times	3-5 times	Others ______
4.	How many times do you reuse a woven/cloth shopping bag?	< 1 time	1 time	2 times	3-5 times	Others ______
5.	What % of the shopping bags do you think that can be recycled with the existing recycling possibilities provided by government:					Others (Pls specify)
	Plastic Bag:	1-10%	11-20%	21-30%	31- 50%	______
	Paper Bag:	1-10%	11-20%	21-30%	31- 50%	______
	Nonwoven bag:	1-10%	11-20%	21-30%	31- 50%	______
	Woven / Cloth Bag:	1-10%	11-20%	21-30%	31- 50%	______
6.	What % of the shopping bags do you think that can be Recycled/ Reused/Sent to Landfill:	Recycle %	Reuse %	Landfill %	Total	
	Plastic Bag:	______	______	______	100%	
	Paper Bag:	______	______	______	100%	
	Nonwoven bag:	______	______	______	100%	
	Woven / Cloth Bag:	______	______	______	100%	
7.	Currently does your government provide recycling system/ policy?	Yes	No			
8.	If your government sets up a recycling policy / system to reduce the landfill%, are you willing to support?	Yes.	No.			
9.	Would you like to place the used shopping bag to the recycling bins provided by your government?	Yes.	No.			

Any other Comments:

Personal Details: (Please underline your selected option)

Age: < 21; 21-30; 30-40; 40-50; >50 Yrs;

Gender: Male / Female;

Profession: Student / Housewife/ Employed/ others;

Education level: Primary school/ Secondary school/ University level/ Postgraduate level/ others

Country: ______________; Place***:*** ___________;

Thank you very much for your precious time spent in filling up this questionnaire.

Appendix-4

Assessment of functional properties – Individual results

1. Tensile Strength

Description	Sample Number	Maximum Load (N)	Tensile strain at Maximum Load (%)	Tensile extension at Maximum Load (mm)
Paper 40g	1	210.200	3.210	2.410
	2	184.830	3.230	2.420
	3	206.570	7.810	5.860
	4	194.890	12.530	9.400
	5	182.950	17.150	12.860
	Average	195.888	8.786	6.590
	SD	11.042	5.420	4.065
	CV%	5.637	61.690	61.678
Paper 75g	1	240.800	3.230	2.420
	2	222.140	7.910	5.930
	3	238.650	13.210	9.910
	4	256.770	3.890	2.920
	5	217.710	2.560	1.920
	Average	235.214	6.160	4.620
	SD	14.036	3.987	2.991
	CV%	5.967	64.717	64.733
Paper 150g	1	260.400	2.550	1.910
	2	257.310	2.570	1.930
	3	301.470	4.560	3.420
	4	256.770	8.550	6.410
	5	286.970	3.130	2.350
	Average	272.584	4.272	3.204
	SD	18.293	2.261	1.694
	CV%	6.711	52.916	52.878
Cotton -1	1	546.300	22.560	16.920
	2	561.870	50.520	37.890
	3	597.580	29.850	22.390
	4	543.620	61.210	45.910
	5	580.400	23.870	17.900
	Average	565.954	37.602	28.202

	SD	20.546	15.486	11.616
	CV%	3.630	41.185	41.188
Cotton -2	1	735.030	37.880	28.410
	2	748.990	38.530	28.900
	3	808.590	37.240	27.930
	4	780.930	39.220	29.420
	5	756.770	38.540	28.910
	Average	766.062	38.282	28.714
	SD	25.963	0.672	0.506
	CV%	3.389	1.754	1.761
HDPE -1	1	98.250	255.220	191.410
	2	104.830	223.200	167.400
	3	90.330	222.550	166.910
	4	104.290	252.540	189.410
	5	102.140	276.470	207.360
	Average	99.968	245.996	184.498
	SD	5.346	20.620	15.468
	CV%	5.347	8.382	8.384
HDPE -2	1	153.950	266.380	199.790
	2	132.340	254.530	190.890
	3	136.240	207.860	155.900
	4	149.530	221.860	166.400
	5	139.590	271.210	203.400
	Average	142.330	244.368	183.276
	SD	8.140	25.091	18.814
	CV%	5.719	10.268	10.266
HDPE -3	1	159.060	262.450	196.840
	2	157.310	264.520	198.390
	3	160.260	301.190	225.890
	4	184.960	296.530	222.390
	5	149.530	361.170	270.880
	Average	165.398	281.173	210.878
	SD	12.037	36.325	27.244
	CV%	7.278	12.919	12.919
LDPE -1	1	59.860	344.400	258.300
	2	55.700	404.530	303.390
	3	68.180	371.870	278.900
	4	55.700	328.540	246.400
	5	60.530	292.510	219.390
	Average	59.994	348.370	261.276

	SD	4.565	38.041	28.526
	CV%	7.609	10.920	10.918
LDPE -2	1	77.040	262.440	196.830
	2	73.020	468.540	351.410
	3	73.550	197.210	147.910
	4	75.970	517.160	387.870
	5	64.020	442.540	331.910
	Average	72.720	377.578	283.186
	SD	4.598	124.713	93.535
	CV%	6.322	33.030	33.030
LDPE -3	1	104.560	411.200	308.400
	2	111.540	353.790	265.340
	3	124.290	373.880	280.410
	4	95.300	341.230	255.920
	5	109.120	374.520	280.890
	Average	108.962	370.924	278.192
	SD	9.462	23.745	17.810
	CV%	8.684	6.402	6.402
PP 40g Sewn	1	143.350	99.890	74.920
	2	153.150	114.550	85.910
	3	137.440	103.210	77.400
	4	131.400	90.540	67.910
	5	142.950	93.850	70.390
	Average	141.658	100.408	75.306
	SD	7.206	8.349	6.259
	CV%	5.087	8.315	8.311
PP 75g Sewn	1	246.300	85.230	63.930
	2	230.730	78.530	58.900
	3	221.870	71.220	53.420
	4	209.260	72.450	54.340
	5	232.750	80.580	60.440
	Average	228.182	77.602	58.206
	SD	12.276	5.200	3.901
	CV%	5.380	6.701	6.702
PP 100g Sewn	1	227.650	49.210	36.910
	2	208.180	45.210	33.910
	3	231.810	57.890	43.420
	4	248.850	65.240	48.930
	5	234.890	57.890	43.420

	Average	230.276	55.088	41.318
	SD	13.144	7.084	5.312
	CV%	5.708	12.859	12.856
PP 40g T-B	1	124.290	114.530	85.890
	2	137.580	99.210	74.400
	3	135.300	93.900	70.430
	4	126.040	81.210	60.910
	5	111.540	87.860	65.900
	Average	126.950	95.342	71.506
	SD	9.253	11.322	8.487
	CV%	7.289	11.875	11.869
PP 75g T-B	1	205.500	71.220	53.420
	2	217.580	88.530	66.400
	3	224.290	106.530	79.890
	4	198.920	88.530	66.400
	5	211.270	82.540	61.910
	Average	211.512	87.470	65.604
	SD	8.887	11.436	8.573
	CV%	4.201	13.074	13.067
PP 100g T-B	1	235.030	69.220	51.920
	2	255.160	61.890	46.420
	3	253.550	73.220	54.920
	4	248.990	68.520	51.390
	5	252.480	79.220	59.420
	Average	249.042	70.414	52.814
	SD	7.293	5.711	4.285
	CV%	2.928	8.111	8.112
PET 40g Sewn	1	67.110	33.240	24.930
	2	75.030	30.540	22.910
	3	73.820	31.180	23.390
	4	62.810	23.150	17.360
	5	63.350	30.540	22.910
	Average	68.424	29.730	22.300
	SD	5.133	3.436	2.579
	CV%	7.502	11.557	11.564
PET 75g Sewn	1	168.720	54.440	40.830
	2	155.160	43.210	32.410
	3	184.020	51.900	38.930
	4	161.870	56.560	42.420

	5	179.320	56.560	42.420
	Average	169.818	52.534	39.402
	SD	10.688	4.968	3.725
	CV%	6.294	9.456	9.453
PET 100g Sewn	1	225.360	30.460	22.850
	2	225.100	32.560	24.420
	3	259.730	34.530	25.900
	4	244.830	37.210	27.910
	5	267.380	33.890	25.420
	Average	244.480	33.730	25.300
	SD	17.310	2.229	1.671
	CV%	7.081	6.608	6.605
PET 40g T-B	1	69.660	19.120	14.340
	2	64.020	31.210	23.410
	3	71.540	31.880	23.910
	4	69.390	30.570	22.930
	5	72.210	27.250	20.440
	Average	69.364	28.006	21.006
	SD	2.880	4.720	3.540
	CV%	4.152	16.853	16.854
PET 75g T-B	1	185.770	51.220	38.420
	2	192.340	59.890	44.920
	3	155.430	51.860	38.900
	4	177.040	57.200	42.900
	5	169.530	51.890	38.920
	Average	176.022	54.412	40.812
	SD	12.873	3.488	2.615
	CV%	7.313	6.411	6.408
PET 100g T-B	1	182.140	43.860	32.900
	2	173.420	45.890	34.420
	3	194.360	45.240	33.930
	4	185.230	43.890	32.920
	5	177.040	43.860	32.900
	Average	182.438	44.548	33.414
	SD	7.218	0.856	0.640
	CV%	3.956	1.920	1.917

2. Tear Strength

Description		Tear Strength (N)
Paper 40g	1	0.590
	2	0.590
	3	0.590
	4	0.590
	5	0.520
	Average	0.576
	SD	0.028
	CV%	4.861
Paper 75g	1	0.810
	2	0.840
	3	0.740
	4	0.740
	5	0.740
	Average	0.774
	SD	0.048
	CV%	6.169
Paper 150g	1	1.040
	2	0.890
	3	0.890
	4	1.090
	5	1.090
	Average	1.000
	SD	0.102
	CV%	10.247
Cotton-1	1	10.080
	2	9.970
	3	9.860
	4	9.200
	5	9.760
	Average	9.774
	SD	0.342
	CV%	3.504
Cotton-2	1	23.030
	2	24.130
	3	24.130
	4	24.650
	5	25.680
	Average	24.324
	SD	0.961
	CV%	3.951
HDPE -1	1	0.520

	2	0.520
	3	0.450
	4	0.590
	5	0.590
	Average	0.534
	SD	0.059
	CV%	10.967
HDPE -2	1	1.040
	2	1.100
	3	0.960
	4	1.030
	5	1.100
	Average	1.046
	SD	0.058
	CV%	5.558
HDPE -3	1	2.770
	2	2.770
	3	2.770
	4	3.050
	5	3.510
	Average	2.974
	SD	0.323
	CV%	10.869
LDPE -1	1	5.790
	2	6.100
	3	5.820
	4	6.100
	5	6.940
	Average	5.953
	SD	0.466
	CV%	7.824
LDPE -2	1	7.420
	2	7.180
	3	7.790
	4	8.510
	5	7.300
	Average	7.640
	SD	0.481
	CV%	6.291
LDPE -3	1	29.600
	2	19.070
	3	18.600
	4	23.220
	5	18.900
	Average	22.623

	SD	4.228
	CV%	18.690
PP 40g Sewn	1	29.700
	2	23.220
	3	19.070
	4	29.600
	5	24.650
	Average	25.248
	SD	4.035
	CV%	15.981
PP 75g Sewn	1	33.550
	2	33.550
	3	30.190
	4	38.140
	5	33.550
	Average	33.796
	SD	2.831
	CV%	8.376
PP 100g Sewn	1	38.580
	2	46.440
	3	35.420
	4	46.850
	5	31.160
	Average	39.690
	SD	6.875
	CV%	17.321
PP 40g T-B	1	16.780
	2	17.250
	3	17.250
	4	14.850
	5	15.340
	Average	16.294
	SD	1.006
	CV%	6.174
PP 75g T-B	1	33.550
	2	27.200
	3	26.900
	4	26.700
	5	20.450
	Average	26.960
	SD	4.146
	CV%	15.377
PP 100g T-B	1	31.650
	2	40.320
	3	45.660

	4	49.410
	5	40.320
	Average	41.472
	SD	5.995
	CV%	14.455
PET 40g Sewn	1	9.360
	2	9.420
	3	7.780
	4	10.750
	5	9.810
	Average	9.424
	SD	0.961
	CV%	10.194
PET 75g Sewn	1	20.380
	2	19.910
	3	21.210
	4	20.450
	5	23.790
	Average	21.148
	SD	1.385
	CV%	6.550
PET 100g Sewn	1	25.680
	2	24.130
	3	23.090
	4	23.610
	5	24.130
	Average	24.128
	SD	0.867
	CV%	3.591
PET 40g T-B	1	9.960
	2	8.220
	3	8.330
	4	12.070
	5	9.600
	Average	9.636
	SD	1.396
	CV%	14.485
PET 75g T-B	1	17.710
	2	17.940
	3	17.710
	4	18.290
	5	18.830
	Average	18.096
	SD	0.424
	CV%	2.343

PET 100g T-B	1	20.590
	2	20.800
	3	22.440
	4	22.040
	5	20.800
	Average	21.334
	SD	0.754
	CV%	3.536

3. Bursting Strength

Description	Sample Number	Bursting Pressure (PSI)	Height of Inflation (mm)	Time to Burst(s)
Paper 40g	1	19.700	3.300	8.000
	2	20.000	2.900	8.000
	3	22.500	3.100	7.000
	4	16.700	3.000	7.000
	5	16.400	3.000	7.000
	Average	19.060	3.060	7.400
	SD	2.270	0.136	0.490
	CV%	11.911	4.433	6.620
Paper 75g	1	23.300	1.900	5.000
	2	23.500	1.800	5.000
	3	17.900	1.500	4.000
	4	22.500	1.800	5.000
	5	18.000	1.300	4.000
	Average	21.000	1.700	4.600
	SD	2.840	0.250	0.550
	CV%	13.480	14.700	11.910
Paper 150g	1	23.600	1.800	5.000
	2	29.200	2.000	6.000
	3	23.700	1.800	5.000
	4	28.800	2.100	6.000
	5	17.900	1.400	4.000
	Average	24.640	1.820	5.200
	SD	4.640	0.260	0.840
	CV%	18.830	14.060	16.090
Cotton -1	1	112.700	5.400	23.000
	2	106.800	5.100	22.000
	3	107.200	5.400	22.000
	4	112.500	5.500	23.000
	5	112.800	5.200	23.000
	Average	110.400	5.320	22.600

	SD	3.100	0.160	0.550
	CV%	2.810	3.020	2.420
Cotton-2	1	124.700	7.100	28.000
	2	125.000	6.900	29.000
	3	125.000	8.900	34.000
	4	125.000	7.300	46.000
	5	125.100	7.100	50.000
	Average	124.960	7.460	37.400
	SD	0.110	0.820	10.040
	CV%	0.090	10.940	26.840
HDPE-1	1	19.300	9.700	11.000
	2	17.500	10.500	7.000
	3	17.500	10.100	7.000
	4	17.500	7.700	7.000
	5	18.200	7.600	7.000
	Average	18.000	9.120	7.800
	SD	0.787	1.372	1.789
	CV%	4.374	15.042	22.934
HDPE-2	1	28.000	8.200	9.000
	2	28.100	9.600	9.000
	3	28.300	7.500	9.000
	4	23.100	6.300	8.000
	5	28.000	9.400	9.000
	Average	27.100	8.200	8.800
	SD	2.260	1.390	0.450
	CV%	8.330	16.980	5.080
HDPE-3	1	35.800	9.500	10.000
	2	35.800	8.100	10.000
	3	30.300	10.000	9.000
	4	30.100	7.800	9.000
	5	34.500	9.600	16.000
	Average	33.300	9.000	10.800
	SD	2.880	1.450	0.840
	CV%	8.649	17.340	9.090
LDPE-1	1	11.700	11.500	6.000
	2	11.900	11.700	6.000
	3	11.900	12.500	6.000
	4	11.900	8.600	6.000
	5	11.900	8.400	6.000
	Average	11.860	10.540	6.000
	SD	0.110	1.900	0.000
	CV%	0.940	18.650	0.000
LDPE-2	1	16.100	8.100	10.000
	2	15.900	7.700	10.000
	3	16.500	8.200	10.000

	4	16.500	8.700	10.000
	5	16.600	10.000	10.000
	Average	16.300	8.400	10.000
	SD	0.290	0.930	0.000
	CV%	1.770	11.000	0.000
LDPE-3	1	23.700	10.000	8.000
	2	23.700	9.600	8.000
	3	24.000	9.100	8.000
	4	18.200	9.400	7.000
	5	18.300	9.500	7.000
	Average	21.580	9.520	7.600
	SD	3.040	0.330	0.550
	CV%	14.110	3.430	7.210
PP 40g Sewn	1	32.200	14.600	10.000
	2	26.800	12.600	9.000
	3	27.400	12.700	9.000
	4	27.100	13.000	9.000
	5	27.100	12.200	9.000
	Average	28.120	13.020	9.200
	SD	2.300	0.930	0.450
	CV%	8.180	7.170	4.860
PP 75g Sewn	1	42.100	11.800	19.000
	2	42.300	12.300	19.000
	3	39.100	12.700	18.000
	4	46.000	13.700	21.000
	5	42.400	12.100	19.000
	Average	42.400	12.500	19.200
	SD	2.450	0.730	1.100
	CV%	5.780	5.810	5.710
PP 100g Sewn	1	66.800	11.100	17.000
	2	72.400	10.900	17.000
	3	72.200	11.200	17.000
	4	66.800	10.600	17.000
	5	71.700	11.100	17.000
	Average	69.980	10.980	17.000
	SD	2.606	0.214	0.000
	CV%	3.725	1.945	0.000
PP 40g T-B	1	27.000	11.200	9.000
	2	27.600	13.800	9.000
	3	32.600	13.500	10.000
	4	32.500	12.800	10.000
	5	27.300	10.800	9.000
	Average	29.400	12.420	9.400
	SD	2.890	1.360	0.550
	CV%	9.830	10.940	5.830

PP 75g T-B	1	45.200	12.000	20.000
	2	43.600	11.800	12.000
	3	44.100	11.300	12.000
	4	43.800	12.500	12.000
	5	43.800	12.500	13.000
	Average	44.100	12.020	13.800
	SD	0.640	0.507	3.493
	CV%	1.452	4.218	25.311
PP 100g T-B	1	59.300	12.500	15.000
	2	65.500	12.500	16.000
	3	55.000	11.200	15.000
	4	60.500	12.300	15.000
	5	56.000	13.300	23.000
	Average	59.260	12.360	16.800
	SD	4.161	0.754	3.493
	CV%	7.021	6.098	20.791
PET 40g Sewn	1	27.300	6.300	8.000
	2	27.300	6.800	8.000
	3	27.300	6.400	8.000
	4	27.100	7.100	8.000
	5	27.000	7.100	8.000
	Average	27.200	6.740	8.000
	SD	0.140	0.400	0.000
	CV%	0.530	5.910	0.000
PET 75g Sewn	1	67.300	8.800	16.000
	2	55.800	9.000	14.000
	3	50.800	8.100	13.000
	4	55.900	7.800	20.000
	5	45.500	7.900	12.000
	Average	55.060	8.320	15.000
	SD	8.072	0.545	3.162
	CV%	14.660	6.550	21.082
PET 100g Sewn	1	84.100	9.000	19.000
	2	73.700	7.500	17.000
	3	67.700	7.300	16.000
	4	52.400	6.600	20.000
	5	57.100	6.900	16.000
	Average	67.000	7.460	17.600
	SD	12.737	0.929	1.817
	CV%	19.011	12.453	10.322
PET 40g T-B	1	21.000	5.600	11.000
	2	24.800	7.000	12.000
	3	24.700	7.000	12.000
	4	21.100	5.900	11.000
	5	21.700	6.200	11.000

	Average	22.700	6.400	11.400
	SD	1.920	0.630	0.550
	CV%	8.460	9.970	4.800
PET 75g T-B	1	56.200	7.900	22.000
	2	58.900	8.300	23.000
	3	62.200	9.600	15.000
	4	51.600	9.100	13.000
	5	53.000	8.500	21.000
	Average	56.380	8.680	18.800
	SD	4.316	0.672	4.494
	CV%	7.656	7.746	23.907
PET 100g T-B	1	54.200	6.900	24.000
	2	64.100	6.900	24.000
	3	56.500	8.500	14.000
	4	57.400	8.200	14.000
	5	68.700	8.000	16.000
	Average	60.180	7.700	18.400
	SD	6.021	0.752	5.177
	CV%	10.004	9.762	28.135

4. Thickness

Description	Sample number	Thickness
Paper 40g	1	0.100
	2	0.060
	3	0.100
	4	0.100
	5	0.060
	Average	0.084
	SD	0.020
	CV%	23.328
Paper 75g	1	0.200
	2	0.220
	3	0.200
	4	0.240
	5	0.200
	Average	0.212
	SD	0.041
	CV%	19.241
Paper 150g	1	0.240
	2	0.220
	3	0.280
	4	0.160

	5	0.300
	Average	0.240
	SD	0.055
	CV%	22.822
Cotton-1	1	0.540
	2	0.540
	3	0.540
	4	0.540
	5	0.560
	Average	0.544
	SD	0.009
	CV%	1.644
Cotton-2	1	0.920
	2	1.120
	3	0.860
	4	1.100
	5	0.900
	Average	0.980
	SD	0.121
	CV%	12.330
HDPE-1	1	0.120
	2	0.100
	3	0.080
	4	0.080
	5	0.100
	Average	0.096
	SD	0.017
	CV%	17.430
HDPE-2	1	0.100
	2	0.140
	3	0.120
	4	0.180
	5	0.140
	Average	0.136
	SD	0.030
	CV%	21.812
HDPE-3	1	0.220
	2	0.240
	3	0.180
	4	0.160
	5	0.120
	Average	0.184
	SD	0.048
	CV%	25.951

LDPE-1	1	0.060
	2	0.040
	3	0.030
	4	0.050
	5	0.040
	Average	0.044
	SD	0.011
	CV%	25.913
LDPE-2	1	0.080
	2	0.080
	3	0.100
	4	0.080
	5	0.100
	Average	0.088
	SD	0.011
	CV%	12.448
LDPE-3	1	0.140
	2	0.120
	3	0.140
	4	0.100
	5	0.140
	Average	0.128
	SD	0.018
	CV%	13.975
PP 40g Sewn	1	0.360
	2	0.320
	3	0.340
	4	0.380
	5	0.340
	Average	0.348
	SD	0.023
	CV%	6.553
PP 75g Sewn	1	0.440
	2	0.500
	3	0.480
	4	0.460
	5	0.440
	Average	0.464
	SD	0.026
	CV%	5.620
PP 100g Sewn	1	0.620
	2	0.600
	3	0.640
	4	0.580

	5	0.620
	Average	0.612
	SD	0.023
	CV%	3.726
PP 40g T-B	1	0.340
	2	0.360
	3	0.360
	4	0.340
	5	0.340
	Average	0.348
	SD	0.011
	CV%	3.148
PP 75g T-B	1	0.520
	2	0.540
	3	0.560
	4	0.580
	5	0.540
	Average	0.548
	SD	0.023
	CV%	4.161
PP 100g T-B	1	0.640
	2	0.700
	3	0.680
	4	0.720
	5	0.680
	Average	0.684
	SD	0.030
	CV%	4.337
PET 40g Sewn	1	0.300
	2	0.280
	3	0.300
	4	0.300
	5	0.300
	Average	0.296
	SD	0.009
	CV%	3.022
PET 75g Sewn	1	0.480
	2	0.500
	3	0.540
	4	0.480
	5	0.480
	Average	0.496

	SD	0.026
	CV%	5.257
PET 100g Sewn	1	0.560
	2	0.500
	3	0.520
	4	0.580
	5	0.600
	Average	0.552
	SD	0.041
	CV%	7.513
PET 40g T-B	1	0.340
	2	0.300
	3	0.320
	4	0.360
	5	0.340
	Average	0.332
	SD	0.023
	CV%	6.869
PET 75g T-B	1	0.580
	2	0.530
	3	0.520
	4	0.480
	5	0.510
	Average	0.524
	SD	0.036
	CV%	6.960
PET 100g T-B	1	0.540
	2	0.560
	3	0.560
	4	0.560
	5	0.580
	Average	0.560
	SD	0.014
	CV%	2.525

5. Areal Density

Description	Sample Number	Weight (g per 100 cm2)
Paper 40g	1	1.067
	2	1.067
	3	1.072
	Average	1.069
	SD	0.002
	CV%	0.221
Paper 75g	1	1.321
	2	1.330
	3	1.322
	Average	1.324
	SD	0.005
	CV%	0.372
Paper 150g	1	1.575
	2	1.591
	3	1.596
	Average	1.587
	SD	0.011
	CV%	0.691
Cotton-1	1	1.871
	2	1.909
	3	1.862
	Average	1.881
	SD	0.025
	CV%	1.326
Cotton-2	1	3.721
	2	3.623
	3	3.705
	Average	3.683
	SD	0.053
	CV%	1.427
HDPE-1	1	0.508
	2	0.508
	3	0.508
	Average	0.508
	SD	0.000
	CV%	0.000
HDPE-2	1	0.737
	2	0.773
	3	0.805
	Average	0.772
	SD	0.034
	CV%	4.409

HDPE-3	1	0.872
	2	0.798
	3	0.835
	Average	0.835
	SD	0.037
	CV%	4.431
LDPE-1	1	0.395
	2	0.397
	3	0.393
	Average	0.395
	SD	0.002
	CV%	0.506
LDPE-2	1	0.758
	2	0.745
	3	0.776
	Average	0.760
	SD	0.016
	CV%	2.049
LDPE-3	1	1.058
	2	0.893
	3	0.904
	Average	0.952
	SD	0.092
	CV%	9.694
PP 40g Sewn	1	0.382
	2	0.334
	3	0.386
	Average	0.367
	SD	0.029
	CV%	7.878
PP 75g Sewn	1	0.713
	2	0.721
	3	0.715
	Average	0.716
	SD	0.004
	CV%	0.581
PP 100g Sewn	1	1.003
	2	1.054
	3	1.080
	Average	1.046
	SD	0.039
	CV%	3.746
PP 40g T-B	1	0.425
	2	0.420
	3	0.422

	Average	0.422
	SD	0.003
	CV%	0.596
PP 75g T-B	1	0.744
	2	0.716
	3	0.770
	Average	0.743
	SD	0.027
	CV%	3.633
PP 100g T-B	1	0.998
	2	1.040
	3	1.050
	Average	1.029
	SD	0.028
	CV%	2.681
PET 40g Sewn	1	0.383
	2	0.394
	3	0.394
	Average	0.390
	SD	0.006
	CV%	1.627
PET 75g Sewn	1	0.678
	2	0.799
	3	0.741
	Average	0.739
	SD	0.061
	CV%	8.185
PET 100g Sewn	1	1.108
	2	1.036
	3	1.154
	Average	1.099
	SD	0.059
	CV%	5.410
PET 40g T-B	1	0.417
	2	0.403
	3	0.371
	Average	0.397
	SD	0.024
	CV%	5.939
PET 75g T-B	1	0.825
	2	0.844
	3	0.877
	Average	0.849
	SD	0.026
	CV%	3.100

PET 100g T-B	1	0.951
	2	1.005
	3	0.890
	Average	0.949
	SD	0.058
	CV%	6.065

6. Air Permeability

Description	Sample number	Air Permeability (mm/s)
Paper 40g	1	0.000
	2	0.000
	3	0.000
	4	0.000
	5	0.000
	Average	0.000
	SD	0.000
	CV%	0.000
Paper 75g	1	0.000
	2	0.000
	3	0.000
	4	0.000
	5	0.000
	Average	0.000
	SD	0.000
	CV%	0.000
Paper 150g	1	0.000
	2	0.000
	3	0.000
	4	0.000
	5	0.000
	Average	0.000
	SD	0.000
	CV%	0.000
Cotton-1	1	203.430
	2	201.190
	3	138.070
	4	147.930
	5	142.020
	Average	166.530
	SD	32.860

	CV%	19.733
Cotton-2	1	40.440
	2	47.340
	3	41.420
	4	41.420
	5	41.420
	Average	42.410
	SD	2.790
	CV%	6.578
HDPE-1	1	0.000
	2	0.000
	3	0.000
	4	0.000
	5	0.000
	Average	0.000
	SD	0.000
	CV%	0.000
HDPE-2	1	0.000
	2	0.000
	3	0.000
	4	0.000
	5	0.000
	Average	0.000
	SD	0.000
	CV%	0.000
HDPE-3	1	0.000
	2	0.000
	3	0.000
	4	0.000
	5	0.000
	Average	0.000
	SD	0.000
	CV%	0.000
LDPE-1	1	0.000
	2	0.000
	3	0.000
	4	0.000
	5	0.000
	Average	0.000
	SD	0.000
	CV%	0.000
LDPE-2	1	0.000
	2	0.000
	3	0.000
	4	0.000

	5	0.000
	Average	0.000
	SD	0.000
	CV%	0.000
LDPE-3	1	0.000
	2	0.000
	3	0.000
	4	0.000
	5	0.000
	Average	0.000
	SD	0.000
	CV%	0.000
PP 40g Sewn	1	788.980
	2	788.980
	3	788.980
	4	788.980
	5	788.980
	Average	788.980
	SD	0.000
	CV%	0.000
PP 75g Sewn	1	788.980
	2	788.980
	3	788.980
	4	788.980
	5	788.980
	Average	788.980
	SD	0.000
	CV%	0.000
PP 100g Sewn	1	552.280
	2	690.350
	3	611.460
	4	615.400
	5	690.350
	Average	631.970
	SD	58.870
	CV%	9.315
PP 40g T-B	1	788.980
	2	788.980
	3	788.980
	4	788.980
	5	788.980
	Average	788.980
	SD	0.000
	CV%	0.000

PP 75g T-B	1	788.980
	2	788.980
	3	788.980
	4	788.980
	5	788.980
	Average	788.980
	SD	0.000
	CV%	0.000
PP 100g T-B	1	463.520
	2	591.730
	3	552.280
	4	749.530
	5	493.110
	Average	570.040
	SD	112.100
	CV%	19.665
PET 40g Sewn	1	788.980
	2	788.980
	3	788.980
	4	788.980
	5	788.980
	Average	788.980
	SD	0.000
	CV%	0.000
PET 75g Sewn	1	788.980
	2	788.980
	3	788.980
	4	788.980
	5	788.980
	Average	788.980
	SD	0.000
	CV%	0.000
PET 100g Sewn	1	502.970
	2	502.970
	3	591.730
	4	611.460
	5	611.460
	Average	564.120
	SD	56.400
	CV%	9.997

PET 40g T-B	1	788.980
	2	788.980
	3	788.980
	4	788.980
	5	788.980
	Average	788.980
	SD	0.000
	CV%	0.000
PET 75g T-B	1	769.250
	2	650.910
	3	788.980
	4	729.800
	5	788.980
	Average	745.580
	SD	58.180
	CV%	7.803
PET 100g T-B	1	749.530
	2	572.010
	3	572.010
	4	572.010
	5	690.350
	Average	631.180
	SD	83.680
	CV%	13.258

7. Water Vapour Permeability

Fabric ID	Specimen	Starting Weight (g)	Ending Weight (g)	Variance (g)	Cover area (m^2)#	Water vapour permeability [g/m^2.day]^	Mean	SD
Paper 40 g	1	89.73	87.58	2.15	0.00302	712.140	680.121	70.290
	2	88.73	86.92	1.81	0.00302	599.522		
	3	89.72	87.52	2.20	0.00302	728.701		
Paper 75 g	1	89.20	87.44	1.76	0.00302	582.961	617.188	33.178
	2	88.27	86.40	1.87	0.00302	619.396		
	3	88.23	86.27	1.96	0.00302	649.206		
Paper 100 g	1	89.82	87.90	1.92	0.00302	635.957	669.080	29.440
	2	88.07	86.02	2.05	0.00302	679.017		

		3	89.65	87.56	2.09	0.00302	692.266		
Cotton-1		1	88.47	85.67	2.80	0.00302	927.438	936.270	8.336
		2	90.00	87.17	2.83	0.00302	937.375		
		3	89.40	86.55	2.85	0.00302	943.999		
Cotton-2		1	88.04	85.24	2.80	0.00302	927.438	948.416	45.214
		2	90.06	87.04	3.02	0.00302	1000.308		
		3	88.97	86.20	2.77	0.00302	917.501		
HDPE-1		1	90.07	89.79	0.28	0.00302	92.744	83.911	10.119
		2	87.02	86.80	0.22	0.00302	72.870		
		3	88.26	88.00	0.26	0.00302	86.119		
HDPE 2		1	89.13	89.08	0.05	0.00302	16.561	17.665	1.912
		2	90.54	90.49	0.05	0.00302	16.561		
		3	88.84	88.78	0.06	0.00302	19.874		
HDPE-3		1	89.47	89.42	0.05	0.00302	16.561	14.353	1.912
		2	90.74	90.70	0.04	0.00302	13.249		
		3	89.84	89.80	0.04	0.00302	13.249		
LDPE-1		1	87.50	87.40	0.10	0.00302	33.123	33.123	3.312
		2	87.60	87.49	0.11	0.00302	36.435		
		3	89.22	89.13	0.09	0.00302	29.810		
LDPE-2		1	89.39	89.30	0.09	0.00302	29.810	27.602	1.912
		2	89.49	89.41	0.08	0.00302	26.498		
		3	89.93	89.85	0.08	0.00302	26.498		
LDPE- 3		1	90.34	90.26	0.08	0.00302	26.498	25.394	14.936
		2	88.25	88.13	0.12	0.00302	39.747		
		3	89.95	89.92	0.03	0.00302	9.937		
PP 40G S		1	86.20	83.30	2.90	0.00302	960.561	983.746	20.148
		2	88.60	85.60	3.00	0.00302	993.683		
		3	88.85	85.84	3.01	0.00302	996.996		
PP 75 G S		1	89.37	86.42	2.95	0.00302	977.122	955.040	44.108
		2	90.17	87.20	2.97	0.00302	983.746		
		3	88.92	86.19	2.73	0.00302	904.252		
PP 100 G S		1	90.50	87.70	2.80	0.00302	927.438	908.668	16.997
		2	89.56	86.86	2.70	0.00302	894.315		
		3	88.51	85.78	2.73	0.00302	904.252		
PP 40G T		1	88.10	85.23	2.87	0.00302	950.624	1003.620	77.891
		2	89.64	86.34	3.30	0.00302	1093.052		
		3	89.20	86.28	2.92	0.00302	967.185		
PP 75 G T		1	88.40	85.52	2.88	0.00302	953.936	936.270	18.243
		2	87.90	85.13	2.77	0.00302	917.501		
		3	87.97	85.14	2.83	0.00302	937.375		
PP 100 G T		1	89.78	86.95	2.83	0.00302	937.375	947.311	8.763
		2	89.79	86.91	2.88	0.00302	953.936		
		3	90.07	87.20	2.87	0.00302	950.624		

PET 40 G S	1	88.28	85.53	2.75	0.00302	910.876	928.542	45.697
	2	87.98	85.28	2.70	0.00302	894.315		
	3	89.12	86.16	2.96	0.00302	980.434		
PET 75 G S	1	89.38	86.40	2.98	0.00302	987.059	936.270	45.936
	2	88.66	85.87	2.79	0.00302	924.125		
	3	88.83	86.12	2.71	0.00302	897.627		
PET 100 G S	1	88.97	86.27	2.70	0.00302	894.315	875.545	24.415
	2	87.56	85.00	2.56	0.00302	847.943		
	3	89.32	86.65	2.67	0.00302	884.378		
PET 40 G T	1	88.57	85.81	2.76	0.00302	914.189	921.917	8.336
	2	88.96	86.15	2.81	0.00302	930.750		
	3	88.44	85.66	2.78	0.00302	920.813		
PET 75 G T	1	89.83	86.88	2.95	0.00302	977.122	956.144	18.243
	2	88.05	85.20	2.85	0.00302	943.999		
	3	88.18	85.32	2.86	0.00302	947.311		
PET 100 G T	1	88.84	85.89	2.95	0.00302	977.122	991.475	24.860
	2	89.13	86.18	2.95	0.00302	977.122		
	3	90.55	87.47	3.08	0.00302	1020.182		

8. pH

Sample no	pH
1. Paper 40g	6.92
2. Paper 75g	6.87
3. Paper 150g	6.84
4. Cotton -1	6.89
5. Cotton -2	Body 9.12 lining 6.20
6. HDPE -1	6.82
7. HDPE -2	6.98
8. HDPE -3	6.94
9. LDPE -1	6.87
10. LDPE -2	6.78
11 LDPE -3	6.91
12. PP 40g Sewn	6.74
13. PP 75g Sewn	6.69
14. PP 100g Sewn	7
15. PP 40g Thermo	6.68
16. PP 75g Thermo	6.62
17. PP 100g	6.64

Thermo	
18. PET 40g Sewn	6.84
19. PET 75g Sewn	6.92
20. PET 100g Sewn	6.86
21. PET 40g Thermo	6.9
22. PET 75g Thermo	6.86
23. PET 100g Thermo	6.88

9. Formaldehyde

Sample no	Formaldehyde Content (* Not detected)
1. Paper 40g	8.87*
2. Paper 75g	8.91*
3. Paper 150g	8.67*
4. Cotton -1	14.06 PPM *
5. Cotton -2	10.87 PPM *
6. HDPE -1	8.48*
7. HDPE -2	8.71*
8. HDPE -3	8.64*
9. LDPE -1	8.82*
10. LDPE -2	8.68*
11 LDPE -3	8.92*
12. PP 40g Sewn	8.78 PPM*
13. PP 75g Sewn	8.68PPM *
14. PP 100g Sewn	5.86PPM *
15. PP 40g Thermo	8.70PPM *
16. PP 75g Thermo	8.74PPM *
17. PP 100g Thermo	8.74PPM *
18. PET 40g Sewn	8.68PPM *
19. PET 75g Sewn	8.62PPM *
20. PET 100g Sewn	8.64PPM *
21. PET 40g Thermo	8.60PPM *
22. PET 75g Thermo	8.64PPM *
23. PET 100g Thermo	8.59PPM *

10. Fibre Content

Sample no	Fibre Content
1. Paper 40g	100% Paper
2. Paper 75g	100% Paper
3. Paper 150g	100% Paper
4. Cotton -1	100% Cotton
5. Cotton -2	Cotton/ Poly 52.5/47.5 (lining: 100% cotton)
6. HDPE -1	100% Polyethylene
7. HDPE -2	100% Polyethylene
8. HDPE -3	100% Polyethylene
9. LDPE -1	100% Polyethylene
10. LDPE -2	100% Polyethylene
11 LDPE -3	100% Polyethylene
12. PP 40g Sewn	100% Polypropylene
13. PP 75g Sewn	100% Polypropylene
14. PP 100g Sewn	100% Polypropylene
15. PP 40g Thermo	100% Polypropylene
16. PP 75g Thermo	100% Polypropylene
17. PP 100g Thermo	100% Polypropylene
18. PET 40g Sewn	100% Polyester
19. PET 75g Sewn	100% Polyester
20. PET 100g Sewn	100% Polyester
21. PET 40g Thermo	100% Polyester
22. PET 75g Thermo	100% Polyester
23. PET 100g Thermo	100% Polyester

Appendix-5

Biodegradability Assessment

Drying of soil

Moisture content checking

Burying of Samples with measuring depth

Buried Samples in the soil bed

Moisture checking after burying samples

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