

EVALUATION OF ECOLOGICAL CRITERIA FOR COTTON TEXTILE  
PRODUCTS

by

Glden Baydar

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EVALUATION OF ECOLOGICAL CRITERIA FOR COTTON TEXTILE  
PRODUCTS

APPROVED BY:

Assoc. Prof. Nilgün Kıran CILIZ. ....

(Thesis Supervisor)

Prof. Dr. Fatoş Germirli BABUNA .....

Prof. Dr. Işıl BALCIOĞLU. ....

DATE OF APPROVAL (26/09/2010)

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## ABSTRACT

Textile industry has tremendous negative impacts on eco-system and human health and material welfare. Both cotton production which is characterized by substantial amounts of agrochemicals and water consumption and wet fabric processing leading to high resource and chemical consumption are important focus points for pollution prevention. The purpose of the study was to interpret total environmental performance of both “conventional T-shirt” and “ECO T-shirt” production for different scenarios with the aid of Life Cycle Assessment (LCA) which is a comprehensive assessment methodology to evaluate the potential environmental impacts of processes, products or services on the environment. In order to assess environmental impacts of selected products, all the analyses were conducted with the aid of GaBi4 software and EDIP2003 (Environmental Design of Industrial Products) assessment methodology. The dye-house applications for the wet processing stage at the selected textile plant have been improved with cleaner production (CP) assessment. As a result of this comparative LCA; it has been proven that environmental impact indicators of acidification, aquatic eutrophication, terrestrial eutrophication, photochemical ozone formation and global warming show significant variations for conventional T-shirt, and ECO T-shirt variants. The contribution of conventional cotton cultivation to the environment has been determined to the highest which is followed by the use stage of both T-shirts.

## ÖZET

Tekstil endüstrisinin eko-sistem, insan sağlığı ve materyal refahı üzerinde son derece negatif etkileri vardır. Yüksek miktarda su ve agrokimyasal tüketimine neden olan pamuk üretimi ve aynı zamanda yüksek miktarda hammadde ve kimyasal tüketimine neden olan boyahane çalışmaları kirlilik önleme kapsamında önemli konulardır. Bu çalışmada dört ayrı senaryoda “konvensiyonel T-shirt” ile “ECO T-shirt” ’ün toplam çevresel performansının değerlendirilmesi; ürün, hizmet ve proseslerin meydana getireceği potansiyel çevresel etkileri değerlendirmekte kullanılan geniş kapsamlı bir değerlendirme metodu olan yaşam döngüsü değerlendirmesi (YDD) ile gerçekleştirilmiştir. Seçilen ürünlerin çevresel etkilerinin değerlendirilmesi GaBi4 paket programı ve EDIP2003 (Endüstriyel Ürünlerin Çevresel Değerlendirmesi) değerlendirme metodu ile yapılmıştır. Seçilen tekstil fabrikasında boyahane uygulamaları temiz üretim (TÜ) değerlendirilmesi ile geliştirilmiştir. Karşılaştırmalı LCA çalışmasının sonucunda, asidifikasyon, akuatik ötrifikasyon, karasal ötrifikasyon, fotokimyasal ozon oluşumu ve küresel ısınma başlıklı çevresel etki kategorileri bakımından Konvensiyonel ve ECO T-shirt varyantları arasında farklılıklar ortaya çıkmıştır. En yüksek çevresel etkilerin konvensiyonel pamuk üretim evresi ve takiben kullanım evresinden kaynaklandığı tespit edilmiştir.

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## LIST OF SYMBOLS/ABBREVIATIONS

<b>Symbol</b>	<b>Explanation</b>	<b>Units used</b>
COD	Chemical oxygen demand	(mg L <sup>-1</sup> )
kg CO <sub>2</sub>	Carbon dioxide equivalents. Units for potential contribution to global warming	(kg CO <sub>2</sub> - eq)
kg NO <sub>3</sub>	Nitrate equivalents. Units for potential contribution to nutrient enrichment	(kg NO <sub>3</sub> - eq)
m <sup>2</sup> UES	Unprotected EcoSystem. Units for potential contribution to eutrophication and acidification	(m <sup>2</sup> UES)
AP	Acidification Potential	
AEP	Aquatic Eutrophication Potential	
CP	Cleaner Production	
CARMEN	Cause effect Relation Model to support Environmental Negotiations	
EDIP	Environmental Design of Industrial Products	
EP	Environmental Impact Potential	
EPI	Environmental Performance Indicators	
FAO	Food and Agriculture Organization	
GHG	Greenhouse Gas	
GWP	Global Warming Potential	
LCA	Life Cycle Assessment	
LCC	Life Cycle Costing	
LCI	Life Cycle Inventory	
LCIA	Life Cycle Impact Assessment	
IKP	Polymer Testing and Polymer Sciences	
ISO	International Standards Organization	
IPM	Integrated Pest Management	
JAS	Japanese Agricultural Services	
NEP	Normalized Impact Potential	
NMVOC	Non-methane Volatile Organic Compounds	
NOS	National Organic Standards	
PE	Person-equivalent	

PES	Polyester
POFP	Photochemical Ozone Formation Potential
RAINS	Regional Air Pollution Information and Simulation
SETAC	Society of Environmental Toxicology and Chemistry
SIC	Standard Industrial Categorization Code
TEP	Terrestrial Eutrophication Potential
WEP	Weighted Impact Potential

## 1. INTRODUCTION

LCA is a decision support tool for evaluating the environmental impacts of products and product systems required for a particular unit of function (UNEP, 2000). The term “life cycle” refers to the major activities in the course of the product’s life span from raw materials acquisition, manufacturing, use, and maintenance, to its final disposal, including transportation between each stage (SAIC, 2006).

LCA methodology was firstly defined by SETAC (Society of Environmental Toxicology and Chemistry) in 1993 and later on standardized by ISO (International Standards Organization) in ISO 14040, 14041, 14042, 14043 series. The methodology consists of four stages: goals and scope definition, inventory analysis, impact assessment and interpretation. The life cycle impact assessment (LCIA) consists of five sub-stages; selection and definition of impact categories, classification (assignment of the emissions to selected impact categories), characterization (conversion and combination of the emissions into representative indicators of impacts), normalization (comparison of the total impacts with a standard for one person) and finally weighting (determination of seriousness of each category) (ISO 14042, 2000).

In fact, LCA is an internationally standardized decision support tool. As noted here, there is no single method for conducting an LCA and the framework is made sufficiently broad to allow the study of wide ranging environmental practices. They are generally conducted for various applications including product development and improvement, strategic planning, evaluation of the pressure of the product on the environment, public policy making and priority settings, marketing, eco- labeling, comparative assessments of products (Guinee, 2002).

Within the framework of the thesis, the study aimed to quantify the major impacts associated with life cycle of conventional cotton T-shirt made of 100% conventionally cultivated cotton using a LCA methodology as a tool for decision making mechanism. Potential environmental impact were evaluated considering cultivation and harvesting for

raw material supply, ginning, spinning, knitting followed by wet fabric processing, service/use and disposal stages of the selected cotton T-shirt.

In order to generate modifications of the product chain which results in impact reduction, an alternative T-shirt production system was developed. In the alternative system, sustainable development principles within cotton cultivation and wet fabric processing operations were taken into account. Environmentally friendly new product was mentioned as ECO T-shirt. In the developed approach 100% organically cultivated cotton was assumed as raw material of product. Moreover, developed alternative ECO T-shirt variants led to evaluation of environmental assessment of agricultural productivity from the point of life cycle perspective.

Taking into account wet fabric processing the major goal was to evaluate water, energy and chemical consumption performances with the intent to conduct material and energy balance analysis for this LCA study. In this sense, two different dyeing recipes were performed and adjusted to conventional T-shirt and ECO T-shirt which show variations from the point of auxiliary, water and energy consumption. CP applications by chemical substitution correspondingly water and energy saving for wet processing resulted in “green dyeing recipe” for ECO T-shirt. Wet fabric processing investigations were performed in a dyehouse, located in Hadımköy, İstanbul in order to acquire site-specific data required for the LCA study. Moreover, the effluent water characterization analyses were carried out at Boğaziçi University, Institute of Environmental Sciences.

Within the above scope, the environmental performance of conventional and variations of ECO T-shirt are analyzed on 1000 items of knitted and dyed cotton T-shirt basis with a total weight of 200 kg and a life span of 3 years covering 50 times washing at a temperature of 60 °C without prewash application. The products were compared with regard to impact categories of acidification, aquatic eutrophication, terrestrial eutrophication, photochemical ozone formation (impact on vegetation) and global warming. The results of the analysis should be regarded as a partial insight into the sustainability of textile production. In order to fulfill complete LCA, GaBi4 software tool was used and all impact evaluations for selected products were made according to EDIP2003 assessment methodology.

## **2. LIFE CYCLE ASSESSMENT AND TEXTILE INDUSTRY**

### **2.1. Sustainability, Cleaner Production and Life Cycle Assessment**

Sustainability has been introduced as a goal of society to ensure that the satisfaction of present needs does not compromise the ability of future generations and to meet their own needs (Zimmermann et al., 2005). In light of rising pressures to adopt a more sustainable approach to product design and manufacture, the necessity to develop sustainable products is one of the major challenges facing industry during the last decade (Maxwell et al., 2003).

Sustainable development or sustainability has three components: environment, economy and social aspects which have to be completely analyzed, evaluated and balanced if a new product is to be designed or an already existing one is to be redesigned (Klöpffer, 2003). The environmental and economic aspects of the sustainability triangle go hand in hand. The trade-off between economic advantage and environmental protection is decreased or even eliminated through CP that leads to production of goods and services at the same or even better quality with less resource and less pollution while improving the bottom-line (Grutter et al., 2004).

As sustainability is defined as a global issue that covers both present and future generations, it requires to measure and describe different aspects of sustainability. The responsibility of the researchers involved in the sustainability assessment is to provide analytic, appropriate, deliberative, holistic and reliable instruments. From an environmental point of view, there is already an internationally standardized tool: LCA which provides a stringent assessment of environmental sustainability (Klöpffer, 2003).

#### **2.1.1. LCA Methodology**

As an unique method LCA involves all processes and environmental releases beginning with the extraction of raw materials and the production of energy used to create the product through the use and final disposition of the product (SAIC, 2006). It has been

firstly defined in 1993 by SETAC as “an objective process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and materials used and wastes released to the environment; to assess the impact of those energy and materials used and releases to the environment; and to identify and evaluate opportunities to affect 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.” (Consoli et al., 1993).

The technical framework for the LCA methodology has been standardized by the ISO. In accordance with SETAC, ISO 14040 defined LCA as “a compilation and evaluation of the input, outputs and the potential environmental impacts of a product system throughout its life cycle”. A typical LCA consists of four stages: Goal Definition and Scope, Inventory Analysis, Impact Assessment and Interpretation, as defined by ISO14040 (ISO 14040, 1997). Figure 2.1 illustrates each stage of a typical LCA and the linkage between them.

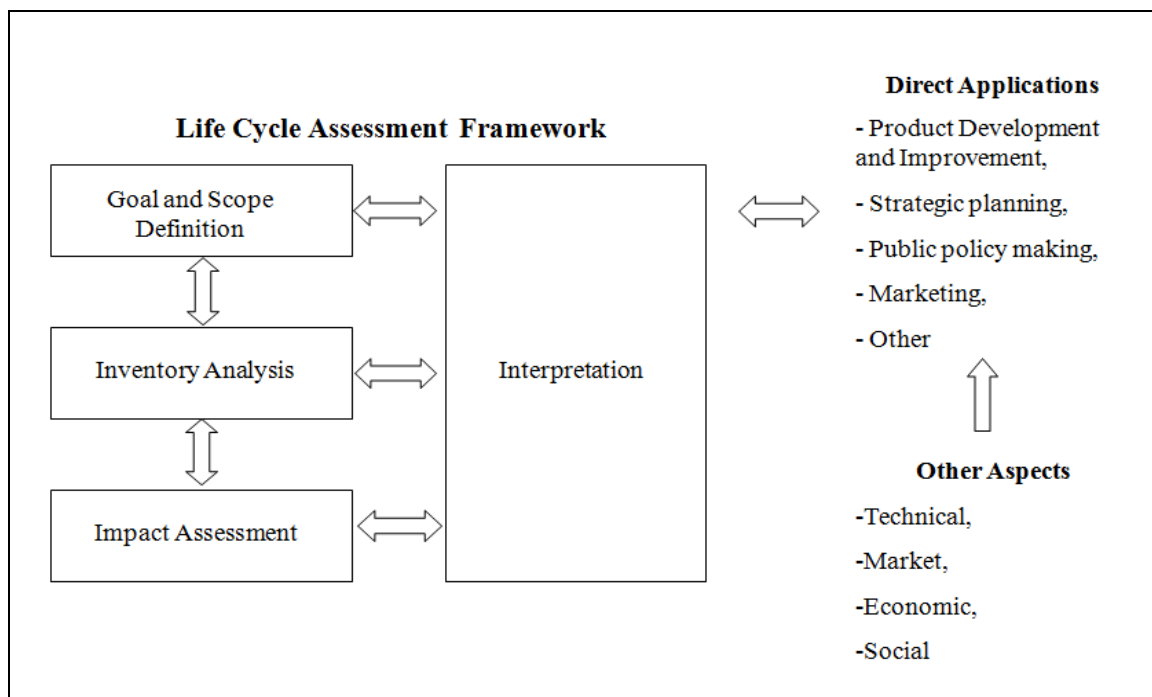


Figure 2.1. LCA framework (ISO 14040, 1997).

LCA has demonstrated to be a valuable tool to document and analyze environmental focus points of products, processes or services that need to be part of decision making towards sustainability (UNEP, 2000). Besides, LCA methodology differs from other environmental assessment methods by basic principles; which are (Klöpffer, 2003):

- the analysis is conducted - from cradle to grave -
- all input/output flows and the potential impacts are structured around a functional unit, - quantitative measurements of the system -
- LCA is essentially a comparative method

2.1.1.1. Goal and Scope Definition. Goal and scope definition is the most important component of an LCA because it has a strong influence on further steps. The study is conducted according to the statements made in this phase (Cederberg et al., 2000).

The goal of an LCA states exact question, target audience and intended application (Guinee, 2002). The scope of the study is characterized in terms of temporal, geographical and technological coverage, and level of sophistication of the LCA in relation to its goal (Giudice et al, 2006). This requires the definition of following items (Jensen et al., 1997):

- the functions of the system, or in the case of comparative studies, systems
- the functional unit
- the product system to be studied and its boundaries
- allocation procedures
- the types of impact and the methodology of impact assessment and subsequent interpretation to be used
- data requirement
- assumptions
- limitations
- the initial data quality requirements
- the type of critical review, if any
- the type and format of the report required for the study

An LCA study is structured around a functional unit, which provides an quantitative reference to which the input and output data are normalised and weighted. Functional unit should be measurable and clearly defined (ISO 14041, 1998).

2.1.1.2. Inventory Analysis. Life cycle inventory (LCI) is a process of quantifying energy and raw material needs, emissions, solid wastes, and other releases for the entire life cycle of a product, process, or activity (SAIC, 2006). Figure 2.2 indicates the possible life cycle stages that can be regarded in an LCA framework and the typical inputs/outputs measured.

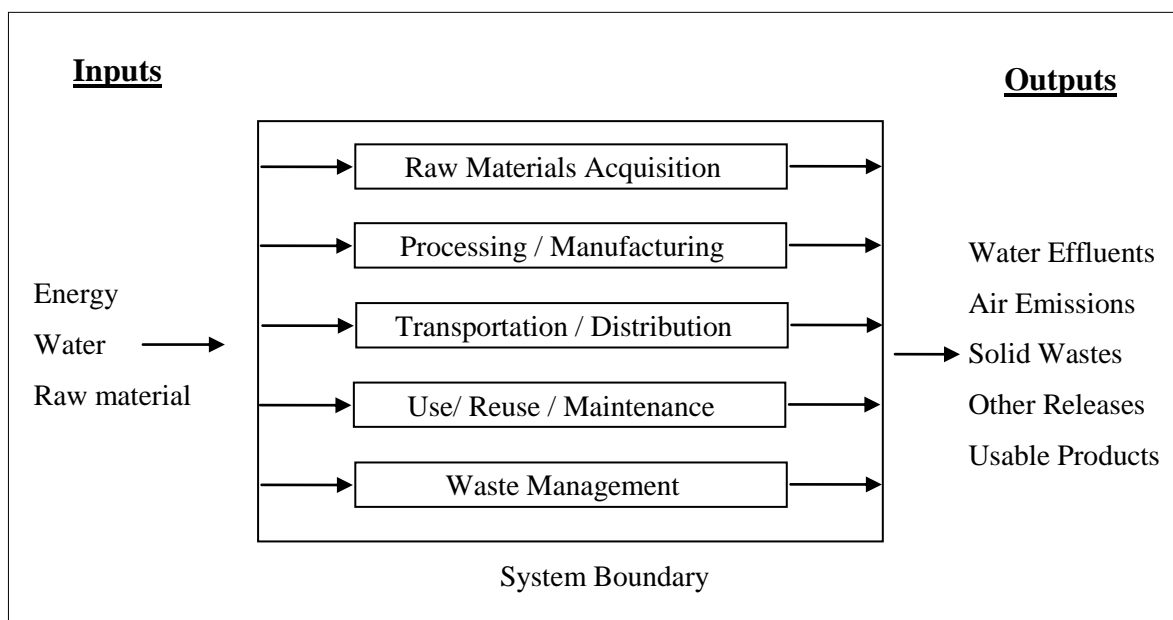


Figure 2.2. System boundary for inventory (SAIC, 2006).

LCI is concerned with the construction of product systems which are composed of unit processes. Quantitative as well as qualitative data are collected for system boundaries of linked unit processes during this stage (Heijungs, 2002). General rules of thumb regarding the quality of data for inventory prescribe the use of (Hauschild et al., 2000):

- recent and quantitative data
- assured and declared data
- specific data whenever relevant and possible for both specific and general LCAs
- general or estimated data when sufficient and when specific data are not available

Inventory analysis is the most time and resource consuming phase of an LCA. Especially the data collection of an LCI is an completely vital because the final results are directly affected by the collected data (Koskela et al., 2004).

A number of sources may be used in collecting inventory data. Starting with the most aggregated, these sources are (Vigon et al., 1993):

- electronic nonbibliographic data bases (government and industrial): averaged industrial data and product specifications
- electronic bibliographic data bases
- LCA software database library (Ecoinvent, GaBi4, SimaPro etc. )
- electronic database clearinghouses
- relevant documents: government reports, open literature papers and books and other lifecycle inventories
- facility-specific industrial data: publicly accessible and nonpublicly accessible,
- laboratory test data
- study-specific data

2.1.1.3. Impact Assessment. “LCIA is a technical, quantitative, and/or qualitative process to define and evaluate the effects of the environmental loadings identified in the inventory phase.” (SETAC, 1990). The influences of the resource use and generated emissions are grouped and quantified into a limited number of impact categories which may then be weighted for importance (UNEP, 2000). Impact assessment should address impact groups of ecosystem health, human health effects and resource depletion (SAIC, 2006).

Current impact assessment methodologies have been developed to evaluate emission inventories for specific regions such as Europe (IMPACT 2002, Eco-indicator 95, Eco-indicator 99, CML, EDIP97, EDIP 2003), the US (TRACI), Canada (LUCAS), and Japan (LIME). The lack of current impact assessment models adapted to other regions is considered as a political and scientific limitation of the current impact assessment practices (Sedlbauer et al., 2007).

EDIP method is a nationally as well as internationally recognized impact assessment method developed by the Institute for Product Development (IPU) at the Technical University of Denmark. EDIP2003 is the update version of the EDIP 1997 impact assessment methodology and both of versions are in compliance with the methodological requirements of the ISO 14040 standard (Wenzel et al., 1997).

As given in ISO 14042, LCIA is conducted within the series of steps. Impact category selection, classification, and characterization are mandatory steps for an LCIA. Normalization, weighting and evaluation are optional elements of LCIA depending on the goal and scope of the study (ISO 14042, 2000). ISO 14042 distinguishes LCIA the following stages:

#### 1) Selection and definition of impact categories

The impact categories are selected and identified in order to describe the impacts caused by the considered product, products or services based on results of inventory analysis. Numerous environmental impact categories have been proposed for life cycle impact assessment such as global warming, stratospheric ozone depletion, acidification, eutrophication, photochemical smog, terrestrial toxicity, aquatic toxicity, human health, resource depletion, land use and water use (Jensen et al., 1997).

#### 2) Classification

In classification, the environmental interventions qualified and quantified in the inventory analysis are assigned to potential impact categories, based on the expected types of impacts on the environment. That is, the data from the inventory table are grouped together into a number of impact categories (SAIC, 2006). In accepted evaluation approach, one source exposes multiple impact categories. Cause-impact network for environmental emissions is shown in Figure 2.3 (Hauschild et al., 2000).

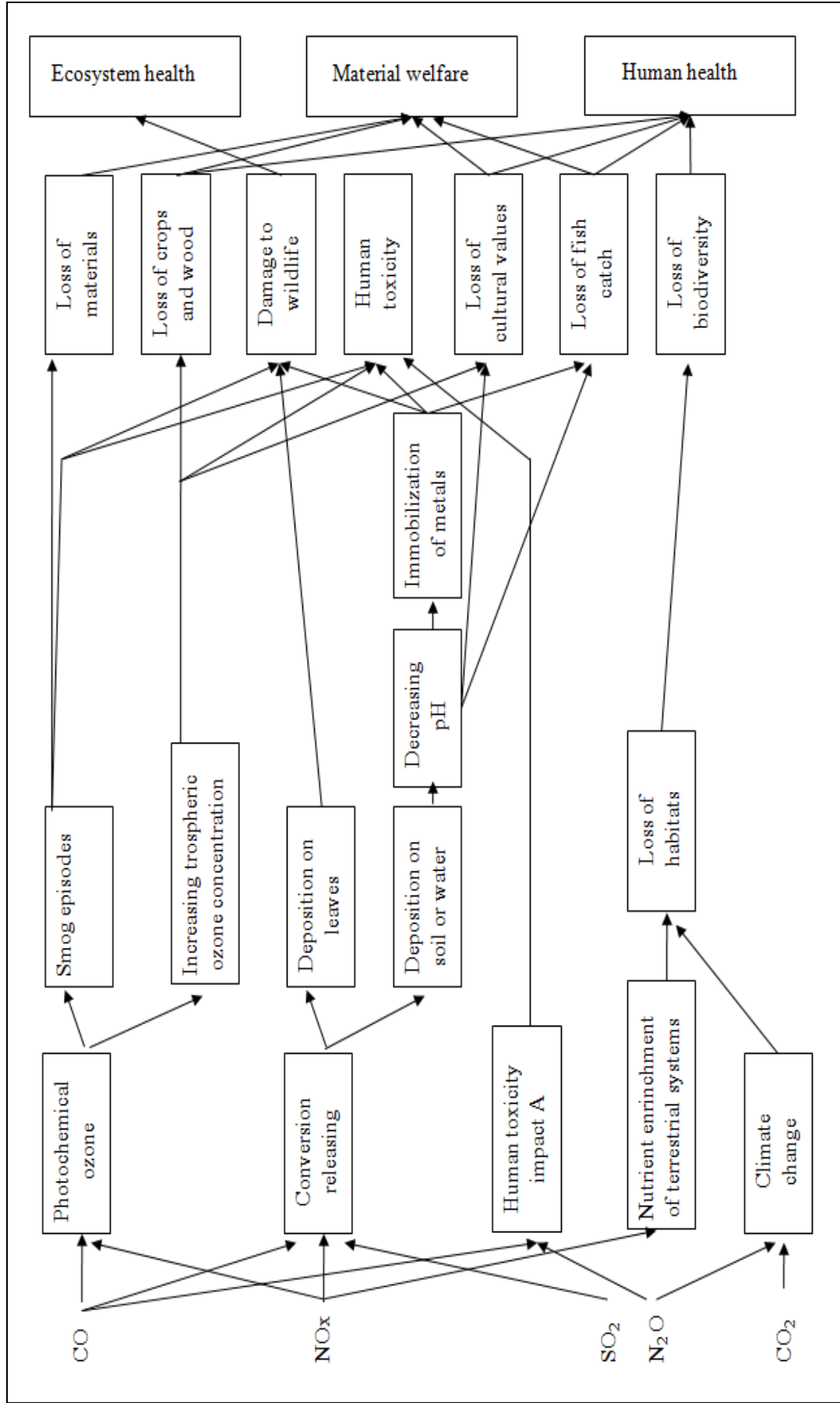


Figure 2.3. Cause-impact network for environmental emissions (Hauschild et al., 2000).

### 3) Characterization

Characterization represents the analysis and estimation of the magnitude of the impacts on the ecological health, human health, or material welfare for each of the impact categories (UNEP, 2000). Impact characterization uses science-based conversion factors, called characterization factors or equivalency factors, to convert and combine the LCI results into representative indicators of impacts. In other words, characterization factors translate different inventory inputs into directly comparable impact indicators (SAIC, 2006).

Environmental impact potential contribution  $EP_{(j)}$  to a given impact category is calculated according to Equation (2.1) (Wenzel et al., 1997).

$$\sum EP_{(j)} = \sum (Q_i * EF_{(j)}) \quad (2.1)$$

where:

$i$  : flow, type

$j$  : impact category, type

$Q_i$  : concentration of material

$EF_{(j)}$  : equivalency (characterization) factor

$EP_{(j)}$  : environmental impact potential

### 4) Normalization

Normalization, the scaling of all impact potentials and resource consumptions using a common reference, has two purposes which are to provide an impression of the relative magnitudes of the potential impacts and resource consumptions, and to present the impact scores to a common reference to enable comparison of different environmental impacts for weighting (Hauschild et al., 2000). This procedure normalizes the indicator results by dividing by a selected reference value which typically refers to impact of the total emission of a reference area (Wenzel et al., 1997). Normalized impact potentials are calculated according to using Equation (2.2):

$$NEP_{(j)} = EP_{(j)} / ER_{(j)} \quad (2.2)$$

where:

$NEP_{(j)}$  : normalized impact potential

$EP_{(j)}$  : environmental impact potential

$ER_{(j)}$  : normalization reference

## 5) Weighting

Weighting, also referred as valuation, is a qualitative or quantitative step and intends to rank, weight, or, possible, aggregate the results of different life cycle impact assessment categories in order to reach at the relative significance of these different results (UNEP, 2000). It is important stage because the impact categories should also reflect study goals and stakeholder values (SAIC, 2006). Weighting may be considered to address three basic aspects (Jensen et al., 1997):

- to define the relative priorities of a group of stakeholders or an organization according to their goals, policies as well as common vision and beliefs
- to ensure that process is visible, documentable, and reportable
- to establish the relative importance of the results

Even if the contributions to two different impact categories are equally large on normalization, this does not mean that the impact potentials are equally serious. The mutual seriousness of impact categories is expressed in a set of weighting factors with one factor per impact category (Hauschild et al., 2000). Method for calculating the weighted impact potential is given in Equation (2.3) (Wenzel et al., 1997).

$$WEP_{(j)} = WF_{(j)} * NEP_{(j)} \quad (2.3)$$

where

$WEP_{(j)}$  : weighted impact potential

$WF_{(j)}$  : weighting factor

$NEP_{(j)}$  : normalized impact potentials

**2.1.1.4. Interpretation.** Life cycle interpretation is the last phase of the LCA and defined as “a systematic evaluation of the needs and opportunities to reduce the environmental burdens associated with energy and raw materials use and waste emissions throughout the whole life-cycle of a product process, or activity.” (SETAC, 1990). Stage also covers conclusions, recommendations, reporting and identification of the important environmental issues consistent with the goal and scope of the study (ISO 14043, 2000).

Life cycle interpretation occurs at every stage in an LCA. If two or more production alternatives are compared and one alternative shows higher consumption of each resource, the interpretation purely based on the LCI can be conclusive (Rebitzer et al., 2004).

### 2.1.2. LCA Software Tools and GaBi4

Computers and adequate software tools are used to support the user in managing and editing LCA studies (Unger et al., 2004). There are 54 different LCA softwares are found in literature. Some of them were compared according to their functionality, flexibility, database, user friendliness, properties, service and cost. According to their evaluation, GaBi4 software to be the best software as showed in Table 2.1 (Dunmade, 2007).

Table 2.1. Evaluation of LCA software tools.

	CUMPAN	EcoPro	EUKLID	GaBi4	KLC-ECO	PEMPS	PIA	SimaPro	Team	Umberto
functionality	+	-	0	++	+	0	-	-	+	++
flexibility	0	0	0	0	0	0	+	0	+	++
database	0	-	0	+	-	0	--	+	++	-
user-friendliness	+	-	0	++	+	-	--	-	0	0
software properties	+	0	0	0	+	0	+	0	-	-
service	++	-	0	++	0	0	--	0	++	+
cost	--	0	-	+	-	0	++	++	--	0

GaBi4 software is developed by the Institute for Polymer Testing and Polymer Sciences (IKP) of the University of Stuttgart in collaboration with PE Europe GmbH. As a method for the assessment of the technical, economic and environment impacts of products, services and systems, comprehensive balances can be used to fulfill ecobalance (or LCA) methods. GaBi4 is different from these methods due to its analysis method, which has been expanded to include technical, environmental, as well as socio-economic aspects (IKP, 2003).

GaBi4 consists of plans, processes and flows as well as their functions form modular units. It provides the modular display of a product's life cycle. Individual life-cycle phases can be grouped in categories and can be processed separately from each other. Simultaneously, balances are calculated based on individual or multiple processes and plans. The transparency of balance results is the major advantage of the GaBi4 (IKP, 2003).

The procedure of GaBi4 is standardized in compliance with the ISO 14040 series. The GaBi4 database is derived from industrial sources, scientific knowledge, technical literature, and internal patent information creating a solid foundation for assessing materials, products, services and processes. Professional, Lean, Extension, Buwal, PlasticsEurope and Ecoinvent databases provide accessing to unit processes as well as to cradle to gate inventories covering different areas like automotive, building and construction, chemicals and petroleum, consumer goods, education, electronics, energy and utilities, food and agriculture, healthcare and life sciences, industrial products, metals and mining, retail, service sector, power generation, transport, and end of life processes (PE, 2010).

### **2.1.3. Applications of LCA**

Today the application of LCA is widespread in industry, research, and policy for various reasons. The applications of LCA can be conducted for various applications including product development and improvement, strategic planning, evaluation of the pressure of the product on the environment, public policy making and priority settings,

marketing, eco- labeling, comparative assessments of products (Guinee, 2002). Some of the recent performed LCA studies are summarized below:

2.1.3.1. Product development and improvement. In order to implement an environmental effective and efficient product innovation policy, LCA is used during the design and construction phase considering whole cycle of the product. In 2005, Protector&Gamble introduced a new laundry detergent, Ariel "Actif à froid" (coolclean). Innovation for a new product was forced by changes in consumer habits and by increasing consumer awareness towards respect of environment. Product development study aimed to provide the desired cleaning performance at a much lower temperature and contribute to society's demand for more sustainable energy use. New product was compared with two old variants in a LCA study. Thus, the study proved that the new product led to important savings in total primary energy consumption (27%) and significantly, had no significant environmental downsides regarding the eleven assessed environmental indicators (Protector&Gamble, 2006).

2.1.3.2. Strategic planning. Results of LCA studies can be used as an instrument for changing management strategies. As an example; waste management strategies are a significant discussion point for textile industry. Morley et al. (2006) evaluated recycling/recovery/reuse options for second hand clothing and it was observed that, in the context of the CO<sub>2</sub> impacts of waste management choices, the reuse of clothing indicates a significant benefit over recycling or disposal. Moreover, Woolridg et al. (2006) demonstrated that for every kilogram of virgin cotton displaced by second hand clothing approximately 65 kWh is saved, and for every kilogram of polyester about 90 kWh is saved.

2.1.3.3. Evaluation of the pressure of the product on the environment. These types of LCAs are conducted to analyze and determine environmental effects of a certain function. Barber et al. (2006) was aimed to determine total energy use and carbon dioxide emissions of New Zealand merino wool. Results showed that merino wool fibre production required a total energy use of 46 MJ/kg half of which occurs on farm and also on-farm activities accounted for two thirds of carbon dioxide emissions. According to another study prepared by Danish Environmental Protection Agency, the resources used and emitted emissions per life cycle

stage were expressed as an inventory but not assessed in terms of LCIA. Study addressed water emissions, energy consumption, toxicity and waste production for acrylic, cotton, wool, viscose and polyester (Loursen et al., 1997).

2.1.3.4. Public policy making and priority settings. Attributes can be affected by the results of LCAs. Marks & Spencer conducted LCA to assess the energy requirements for life cycle of a pair of pleated polyester trousers and a pack of men's cotton briefs. Boundaries for two products included production, manufacturing, consumption, collection, transport, use and waste/recovery. According to findings, consumer use corresponds to 76% and 80% of the life cycle energy needs respectively (Collins et al., 2002). Similarly, a simplified LCA supported previous study. The study aimed to ascertain the impact of domestic laundering on the life cycle of cotton towels and found that consumer use accounts for 76% extracted energy consumption of towels over lifetime. Study was also proved that any process that could diminish the washing frequency of product would be likely to influence an important reduction in energy, water and chemical consumption (Blackburn et al., 2004).

2.1.3.5. Marketing. As result of increasing environmental consciousness, LCA is being used by many companies to increase their market share. Design Mobel won 2007 NZI National Sustainable Business Awards. Company conducted a full LCA of products from raw material inputs, through manufacturing, to the use of waste by-products and design briefs. They sourced wood from sustainable forestry operations and used natural materials including bamboo, cotton, 100% natural latex and wool in natural manufacturing processes (SBN, 2008).

2.1.3.6. Eco-labelling. Results of LCA studies can be used to set up or revise eco-labeling criteria for products or services. In 2002, environmental 'hot spots' in the chrome-tanned bovine leather industry were detected with the aid of LCA study and study pointed out that global warming, photochemical ozone formation, acidification and nutrification resulting from CH<sub>4</sub> and NH<sub>3</sub> in the landfilling of hide wastes produced in the tannery were of concern. The Autonomous Government of Catalonia used the results of LCA to establish the environmental criteria that a leather product must fulfill in order to attain the Catalan eco-label (Canals et al., 2002).

2.1.3.7. Comparative assessments of products. Comparative LCAs are made to identify the more environmentally friendly way of fulfilling a function and illustrate the actual difference between products. University of Cambridge Institute for Manufacturing evaluated cotton, viscose and nylon fibres with polypropylene and latex-foam backing with the aid of LCA. Energy use; use of toxic chemicals; release of chemicals in waste water; and solid waste were assessed and also social issues were discussed within the frame of the study. Results pointed out that the key environmental impacts of the sector resulted from the use of energy and toxic chemicals (Allwood et al., 2006). In another investigation, European Textile Services Association observed entire life cycle of hand-drying systems from forestry and cotton farming, through towel production and use, up to recycling or final disposal. For this purpose cotton towels were compared with paper towels made from virgin luxury paper and when they were compared with paper towels made from 50% recycled paper. Under the study's conditions, it was concluded that cotton was found more environmentally friendly especially from energy, resultant waste, global warming potential, acidification potential and eutrophication potential point of view (E.T.S.A., 2006). In the U.K., environmental impacts associated with using disposable nappies and reusable nappies were evaluated with the aid of life cycle methodology. Due to scope of the study, boundary covered entire life cycle of nappies systems from production to disposal. Results determined global warming, acidification and non-renewable resource depletion impacts as the major impact areas and none of the functional unit studied were more or less environmentally preferable (ERM, 2005). Moreover, Chalmers University of Technology in Sweden conducted a LCA for three fabrics types for a sofa made of conventional cotton, Trevira CS (a flame retardant polyester) and wool/polyamide. Thus, study concluded that Trevira CS was preferable in terms of minimizing environmental impact when choosing between the three fabric types and the cotton sofa cover was a less favourable choice. In terms of cotton fabric, project indicated that the most significant impact was cultivation and wet treatment of the fabric (Dahllöf, 2004). Protector&Gamble compared environmental profiles of five types of its laundry detergents -the Ariel brand- regular powder, compact powder, powder tablets, compact liquid, and liquid unit dose systems by using LCA methodology and found that both compact liquid and compact powder detergents were environmentally preferable detergent formulations, mainly due to the lower use of chemicals, resulting in benefits on aquatic toxicity, eutrophication, ozone depletion and photochemical smog compared to other detergent forms and less pronounced

benefits of compact forms were also investigated on energy requirements and on impact categories of acidification, human toxicity and climate change (Van Hoof et al., 2003). Moreover, Kalliala et al. (1999) compared and evaluated different hotel textiles: cotton and cotton-polyester sheets and it was found that cotton-polyester sheets in hotel use have fewer environmental impacts than cotton sheets. This was due to the higher durability as well as lower laundering energy requirements of cotton-polyester sheets. Potting et al. (1995) took into account four types of floor covering: linoleum, cushion vinyl, tufted carpet with a woollen pile and tufted carpet with a polyamide pile were investigated with respect to their environmental impact. According to the results, linoleum was to be the most environmentally favourable floor covering and environmental impacts of cushion vinyl, tufted carpet with a woollen pile and tufted carpet with a polyamide pile were nearly same.

## **2.2. Textile Industry**

The textile and clothing sector consists of a wide number of sub-sectors including the whole production cycle from sourcing of raw materials (fibers) to semi-processed (yarns, woven and knitted fabrics with their finishing process) and final consumer products (carpets, home textiles, clothing and industrial use textiles). The complexity of the sector complicates a clear-cut classification system for the different activities involved (EC, 2001).

The sector is grouped under six main sub-categories in the European Commission Best Available Techniques for the Textiles Industry. These categories are defined as Yarn and Thread, Woven Fabric, Textile Finishing, Home Textiles, Industrial & Other Textiles (which includes Carpets and Wool Scouring) and Knitted Fabrics & Articles (EC, 2001). On the other hand; structure of sector is broken down into nine categories which includes approximately 6000 facilities by three-digit standard industrial categorization code (SIC) as Broadloom Mills (Cotton), Broadloom Mills (Man-Made Fibers), Broadloom Mills (Wool), Narrow Fabric Mills, Knitting Mills, Textile Finishing, Carpets and Rugs, Yarn Thread Mills and Miscellaneous Textile Goods (U.S.EPA, 1996).

### 2.2.1. Textile Raw Materials and Cotton

Fibers used in the textile industry are classified into two main categories: natural and man-made (U.S.EPA, 1996). In 2007/08 period, man-made fibers and natural fibers shared about 60.7% and 39.3% of global textile fiber consumption respectively. Cotton is the most consumed natural fibre of the world, accounting for about 37.5 % of global fibre consumption while 42.3% is taken up by polyester and the rest accounted for by other fibres as represented in Table 2.2 (Oerlikon, 2008).

Table 2.2. World textile fiber consumption in 2007/08 (Oerlikon, 2008).

Type of fibre	Share %	Production, thousands of tons
Man-made		44.086
polyester	42.27	30.685
polyamide	5.56	4.037
acrylics	3.33	2.422
cellulosics	5.11	3.712
others	4.45	3.230
Natural		28.502
cotton	37.47	27.203
wool	1.65	1.201
silk	0.13	98
Total	100	72.588

Cotton is the fruit of a shrubby plant commonly referred to as the "cotton plant", which is grown annually. Cotton fiber, grows in a form a ball, consists of long, fine, flattened and convoluted hairs called 'lint', which can be detached easily from the seed of the cotton plant (Kooistra et al., 2006; UNCTAD, 2002).

### 2.2.2. Cotton Production Overview

Today, cotton provides about 37.5% percent of all global fiber requirements and it is grown in more than 80 countries, approximately 33.2 million hectares (Oerlikon, 2008; USDA, 2008). The latest figures for the 2007/08 season show world raw cotton production at 26.1 million tones with five countries: China, India, USA, Pakistan and Brazil, accounting for 80 % of total production. The remainder is spread across a large number of much smaller producers like Turkey, Uzbekistan Syria, Greece. Global cotton production of 2007/08 season is detailed in Table 2.3 (USDA, 2008; Chapagain et al., 2006).

Table 2.3. Main cotton producers in 2007/08 (USDA, 2008; Chapagain et al., 2006).

Countries	Avarage production (million tonnes/year)	Avarage lint production (kg/ ha)	Hectares cropped to cotton( $\times 10^6$ )	% of world production	Planting period
China	8.1	1299	6.20	31	April/May
India	5.2	561	9.55	19.9	April/May
USA	4.2	985	4.25	16	March/May
Pakistan	1.9	646	3.0	7.2	May/June
Brazil	1.6	1488	1.08	6.13	October
Uzbekistan	1.2	826	1.45	4.5	April
Turkey	0.7	1298	0.52	2.6	April/May
Greece	0.3	916	0.32	1.1	April
Australia	0.3	2077	0.07	1.1	October/November
Syria	0.2	1252	0.20	0.7	April/May

### 2.2.3. Cotton Cultivation

Although cotton is native to tropical and subtropical regions, it is grown in a very broad range of climates, soils and cultural practices, even within a given district (Cherrett et al., 2005). The key elements for succesful cotton growing are: temperature, sunlight,

soil, supplemental nutrients, crop protection, rainfall and irrigation (Loursen et al., 1997). These are described as follows:

2.2.3.1. Temperature. Cotton is a difficult crop to grow because it is sensitive to drought and low temperatures. Although its resistance varies from species to species, it is primarily grown at temperatures between 11°C and 25°C (UNCTAD, 2002).

2.2.3.2. Soil. Cotton plant is grown on a wide range of soils but medium and heavy textured, deep soils with good water holding capacity are preferred to productive cultivation (Kooistra et al., 2006).

2.2.3.3. Rainfall and Irrigation. Cotton is the most water-intensive crop and it is estimated that cotton growing results in 1-6% of world's total freshwater withdrawal. Required water is provided by rainfall or irrigation. Irrigation, strongly increases yield, is applied to 53% of the world's cotton fields where normal precipitation rate is not enough for water requirements of crop being cultivated (Soth et al., 1999). In order to produce 1 kg of cotton lint, 10,000-17,000 liter of water is needed (Kooistra et al., 2006). According to Soth et al. (1999), water requirement is in the range of 7,000 - 29,000 litres per kg cotton lint production. In fact, water consumption largely depends on irrigation technique. With technical innovations like drip irrigation, extensive water demand for cotton production could be cut down to 7,000 litre/ kg-lint (Soth et al., 1999).

2.2.3.4. Soil Fertility. The cotton plant is particularly weak and nutrient uptake is remarkable for cultivation. In order to increase organic matter content in the soil, cotton cultivation operation requires some soil management practices including physical adjustments to soil, use of organic manure and composts, animal manure additions, cover cropping, crop rotation, rock phosphate, muriate of potash, gypsum, lime, etc. (UNSDAC, 2002; Loursen et al., 1997; OE, 2008b). Due to the extensive variability in the cotton growing conditions, it is very difficult to generalize requirements for cotton fertility management (Silvertooth, 2002). In this context, fertilizer application is an integral part of cotton production and a crucial factor in realising an optimum yield under any set of agroclimatic conditions and practices (Cherrett et al., 2005).

Common synthetic fertilizers used in fertility management are typically combinations of nitrogen (N), phosphorus (P) and potassium (K) (Silvertooth, 2002). The nutrient requirements of cotton under irrigation are 100-180 kg/ha nitrogen (N), 20-60 kg/ha phosphorus (P) and 50-80 kg/ha potassium (K) (Kooistra et al., 2006).

Nitrogen (N) is usually given in ammonium, nitrate or amide form. It increases height of plants, boll-bearing capacity and seed weight, and also it improves seed-cotton yield. In order to improve root development, water use efficiency, the energy balance and the weight, oil and protein contents of the seed as well as fibre quality, phosphorus (P) is applied before or at planting period in form of superphosphate, ammonium phosphate or ammonium nitrate phosphate. Potassium (K) is normally added as potassium chloride and also where sulphur is lacking, as potassium sulphate. Potassium improves fibre fineness and strength, and results in early maturity of the crop (Silvertooth, 2002).

Crop rotation is an alternative practice to fertilizer application for achieving soil fertility (Guerena et al., 2003). Benefits of crop rotation cotton-based farming systems are reduction of soil erosion, physical, chemical and biological degradation, water and energy conservation, timeliness of land preparation, and management of weeds, pests and diseases. Wheat is the most commonly used crop in rotation with cotton (Hulugalle et al., 1997). Cover cropping is another sustainable approach used to manage soil fertility, soil quality, water, weeds, pests and diseases in cultivation. Crimson clover, field peas, and hairy vetch are some of the winter cover crops for nitrogen production in cotton cultivation (Guerena et al., 2003).

2.2.3.5. Crop Protection. Cotton is very prone to insects, diseases and weeds that can damage the cotton crop and cause yield losses. In order to protect the cotton plant, large quantities of acutely toxic chemical pesticides are used in cultivation. The types, amounts and application frequency of chemical pesticides vary widely from country to country (Myers et al., 1999).

The high share of pesticide use is only a quantitative aspect. According to WHO, most pesticides used for cotton are classified as hazardous. The use of these pesticides are risk for workers, animals and ecosystems that are linked to the cotton fields either directly or

indirectly (Soth et al., 1999). Recently, it is estimated that cotton cultivation consumes 11% of the world's pesticides and pesticide costs form more than or close to 50% of the total cost of seed cotton production (Myers et al., 1999; ICAC, 1994).

#### 1) Insects Control and Protection Against Insects:

Cotton insects are the principal reason of yield losses and it is estimated that 15% of world annual crop production is lost due to insect infections (UNSDAC, 2002). Insect control strongly relies on intervention with a wide variety of chemical insecticides (Loursen et al., 1997). Effectiveness of a particular insecticide can vary greatly from field to field, depending on previous insecticide use, pest species, and levels of resistance (Catchot, 2007). Predominant class of insecticides listed in Table 2.4 (Kooistra et al., 2006).

Table 2.4. Major insecticides used in cotton cultivation (Kooistra et al., 2006).

Designation of the substance	Chemical group of the substance	Toxicity Class ( WHO )*	Share (%) in the global cotton insecticide market
Deltamethrine	Pyrethroid	II	12
Lamda-Cyhalothrine	Pyrethroid	III	9
Monocrotophos	Organophosphorus	Ib	9
Alpha-Cypermethrine	Pyrethroid	II	8
Chlorpyrifos	Organophosphorus	II	7
Esfenvalerate	Pyrethroid	II	7
Methamidophos	Organophosphorus	Ib	6
Dimethoate	Organophosphorus	II	5

\*Ib: highly hazardous; II: moderately hazardous; III: slightly hazardous

In order to achieve an effective and successful insect control mechanism, Integrated Pest Management (IPM) stimulates reduction in insecticide consumption by using some pest control options. These methods include biological, cultural, chemical control and varietal selection (Catchot, 2007).

## 2) Weed Control and Protection Against Weed

Weed is another important issue for cotton cultivation and requires a sound weed control program. Cotton yields and harvesting efficiency can be reduced by as much as 30 percent by weeds (Anthony et al., 1994).

The method used will be dependent upon local circumstances. Hand hoeing and the use of flame cultivation is a method used in weed management. Mechanical tillage can be employed in the form of preplanting tillage and post planting tillage (Loursen et al., 1997). Among other weed control methods, the popularity of herbicides can be attributed to their effectiveness in controlling a wide range of weed species. Application of herbicides may be made at six critical stages in the production of cotton, these are foliage of existing weeds, preplant soil incorporation, preemergence, directed postemergence, over-the-top postemergence and last postemergence (Anthony et al., 1994). The most important herbicides used in cotton cultivation are listed in Table 2.5 (Kooistra et al., 2006).

Table 2.5. Major herbicides used for cotton cultivation in 1997 (Kooistra et al., 2006).

Designation of the substance	Chemical group of the substance	Toxicity Class ( WHO )*	Applied area (%)
Trifluralin	Dinitroanilin	U	55
Msma	Organoarsenic	n.l.	29
Fluometuron	Substituted urea	U	44
Pendimethalin	Dinitroanilin	III	28
Diuron	Substituted urea	U	12
Prometryn	Substituted triazine	U	19
Cyanazine	Substituted triazine	Ib	18

\*Ib: highly hazardous; III: slightly hazardous; U: unlikely to be hazardous; n.l.: not listed

## 3) Diseases of Cotton and Protection Against Diseases

Organisms responsible for cotton diseases include fungi, bacteria, nematodes, and viruses. These diseases may be grouped as seedling diseases, soil diseases, boll diseases,

and foliar diseases (Guerena et al., 2003). Disease control strategies vary, but are designed to reduce pathogen inoculum or restrict development of the pathogen in host tissue. Modification of cultural practices such as planting, fertilisation, irrigation, crop rotations, tillage, harvesting and use of fungicide may be employed (Loursen et al., 1997).

#### **2.2.4. Types of Cotton Production**

Within all the different management systems, a few distinguish themselves by certified organic and reduced insecticide input/integrated pest management (IPM). Management systems that are not IPM or organic are considered to be conventional (Kooistra et al., 2006). These three main approaches to cotton production are summarized below:

2.2.4.1. Conventional Systems. Today, conventional cotton farming systems represents nearly 80% of whole world's production. Conventional farming includes a wide range of farms since size, agrochemical inputs/outputs, energy efficiency, production efficiency and the related environmental impact differ enormously among farms (Kooistra et al., 2006).

2.2.4.2. IPM Systems. In 1967, Food and Agriculture Organization (FAO) defined Integrated Pest Management (IPM) as “a pest management system that, in the context of the associated environment and the population dynamics of the pest species, utilizes all suitable techniques in as compatible a manner as possible and maintains the pest population at levels below those causing economic injury.” (FAO, 1967).

IPM aims to use non-chemical crop protection methods of suppressing insect population; to monitor pest populations; and when scouting indicates that pest populations have exceeded economic thresholds allows the use of chemical pesticides, even easily degradable and less toxic ones, when there is a need. It seeks to suppress pest populations through a combination of biological control (using naturally occurring parasites and predators as major regulators of insect populations), cultural control (removal of weeds, harvest residues), chemical control (using different types of insecticides to reduce the likelihood of resistance to any one chemical building up) and varietal selection (consideration of insect resistance/tolerance cotton plant varieties) (Catchot, 2007).

2.2.4.3. Organic Systems. Organic cotton, also referred clean, natural, green or environment-friendly cotton, originates from organic agriculture (ICAC, 1994; Ton, 2007). European Community Council Regulation EC 2092/91 defined organic agriculture as “Organic production systems are designed to produce optimum quantities of products of high quality by using management practices which aim to avoid the use of agro-chemical inputs and which minimize damage to the environment and wildlife” (2092/91/EEC, 1993).

Governments and regions have their own country or region specific organic production standards. The most commonly adopted standards are the European Union’s EU Regulation 2092/91, the United States Department of Agriculture’s National Organic Standards (NOS) and the Japanese Agricultural Services’ (JAS) standard. In order to certify an agricultural product as ‘organic’, one or more of these regulations, an accredited, independent, third-party certifier must review the farming project and its operations to ensure that it meets the requirements for the particular standard as well as the additional standards for dual or multi-certification. A standard lays out a set of conditions for the farming and/or processing of a product. A certifying agency confirms that the conditions of the standard have been met and is accredited by the body that created the Standard (OE, 2007; Ton, 2007).

Organic cotton production is a system of growing cotton without synthetic chemical fertilizers, herbicides, insecticides, growth regulators, growth stimulators, boll openers or defoliant (Ingram, 2002). In order to be eligible for certification as organic cotton, cotton must be grown without the prohibited chemicals for a period of three years. Cotton produced without prohibited chemicals in the first and second years is referred as transitional, pending certification or organic certified B cotton (ICAC, 1994). Although, organic cotton has been cultivated for centuries, the first certified organic cotton production dates back to 1989/90s which was cultivated in Kahramanmaraş/Turkey. The project was called Good Food Foundation and followed by a second multinational project initiated in Salihli (Manisa) by Rapunzel, a German company (ICAC, 2003).

The process of transition from conventional management is fraught with risk and requires a significant amount of time to learn the trade of organic production. Hanson et al.

(2004) defined a wide range of risks facing the United States organic farmers who participated in group discussions during in 2001 and 2002. According to qualitative gathered information, concerns of organic farmers were grouped under five main categories which were mainly production risks, risk of the use of genetically modified organisms, input risks, organic marketplace risks and finally the agricultural policy risks.

Among the issues discussed in the studies related to the organic cotton supply chain, cost of production of organic cotton versus conventional cotton and yield of organic cotton production are the most common evaluation criteria encountered in the literature.

The development of infrastructure for organic cotton training, extension, certification, research and capacity building, and extension is costly. So, in the context of net return from the production system, these are the additional parameters considered by farmers in the decision-making process about switching to organic production (Ton, 2007).

A case study conducted by Lanting et al. (2005) in the region of Karimnagar, India found that profitability of an organic cotton farm compared with its conventional counterpart was significantly higher. Lanting et al. (2005) attributed the relatively higher profits mainly to the reduced pest management methods implemented for organic farming. While in organic farms, the cost of pest management was an average of Rs. 220 per acre, organic method of farming bans the use of synthetic pesticides and saved the cost of the 1404 Rs of pesticide typically applied per acre under conventional practices.

Another practice of organic cotton cultivation initiated in India made a reduction in overall input costs by 60% after switching from conventional to organic farming. Reduced costs were subject to substitution of herbicides under organic practices. With the absence of herbicides, organic farming relies on hand-weeding that result to high labor requirements. While manual labor is accepted as a major challenge for the spread of organic cotton in developed western countries, it is an opportunity for developing countries, where sufficient and inexpensive labor is available. In this case, labor costs were compensated by reduced other external input costs (Lakhal et al., 2008). This result was supported by Eyhorn et al. (2007) for India, where the variable production costs in organic compared to conventional cotton farming tended to be lower by 13% in 2003 and were

lower by 20% in 2004. On the other hand, Swezey et al. (2006) concluded a six-year research in the northern San Joaquin Valley of California that indicated operational costs of production per bale were 37% higher for organic cotton when compared with conventional counterpart. This increased costs depended on lower yields in the organic system. However, when calculated per hectare, costs of production were not statistically different, being only 5% higher for organic fields. In addition, a case study performed in Viotia - Greece revealed that overall costs of conventional cotton farming are not importantly different from the costs of farming organic cotton (Tzouvelekas et al., 2001). Moreover, another comparative case study of organic and conventional cotton cultivation performed in Egypt revealed that operational costs 1.5% higher for organic cotton when compared with conventional cotton (Crucefix, 1998).

A case study conducted by PAN UK analyzed the impact of organic cotton production on the livelihoods of farmers in sub-Saharan Africa. The research results showed that the reduction in inputs and relatively high output when compared with conventional cotton made organic cotton an economic and attractive option for farmers (Ton, 2002). This result was corroborated by Ramesh et al. (2010) for India, where a reduction in cost of production and increased gross and net returns for organic cotton cultivation compared to conventional counterparts were observed.

Another crucial factor in decision making is to overcome the loss of organic cotton cultivation yield affecting net return in the absence of synthetic fertilizers, herbicides, insecticides and growth regulators (ICAC, 1994).

With yield as the basis of comparison, the first few years after conversion to organic production yields can be reduced by up to 50% but three years later yields production rate returned to the same levels as conventional, an even few cases even higher (Kooistra et al., 2006; OE, 2007; Lakhal et al., 2008). However, recent findings suggest that low-input cotton cultivation systems can even have equal or slightly higher production as compared to conventional production systems. Lanting et al. (2005) found that cotton yields in organic farms were 12% higher than in conventional farms. Eyhorn et al. (2007) concluded that after completing a 2–3 year conversion period, organic cotton yields could provide 5% to 10% higher production rate in 2003 and 2004. Successfully managed organic cotton

projects in Benin, Mali and Senegal also demonstrated that, over time, yields increase and organic growers achieve similar yields to conventional growers (Glin et al., 2006). Another long-term study initiated in Alabama on organic cotton pointed out that by using annual winter legumes, cotton yields were equivalent to those grown using N fertilizer (Guerena et al., 2003). Lower yields however, were found in organic farms in northern San Joaquin Valley of California. Significant six-year average yield differences between organic and conventional farms were 2.3 bales ha<sup>-1</sup> (34% reduction) in organic yields compared to conventional yields (Swezey et al., 2006). The same is true in Greece where organic cotton yields were lower (27%) than conventional farms (Tzouvelekas et al., 2001). Moreover; it was shown that after two years, organic cotton yields were 7% lower compared to the conventional average yield for Egypt (Crucefix, 1998).

Today, certified organic cotton is grown in 22 countries, grown on 161.000 hectares in the world. In 2007-2008 crop year, the amount of organic cotton production worldwide has risen to 145.872 tons of fiber - representing a 152% increase over production in the previous year. The top five organic cotton producing countries, in order of scale India (51%), Syria (19%), Turkey (17%), China (5%) and Tanzania (2%). Together, these five countries accounted for 94 percent of world production. Despite this spectacular growth, the volume of organic fiber traded on the international market still represents only 0.2 % of global cotton fiber production (OE, 2008a).

Turkey contributed to 32.76% and 39.76% of the global organic cotton production in 2005/06 and 2006/07 growing seasons respectively (OE, 2007; OE, 2006). However, it is difficult to establish reliable data about the cultivation and consumption of organic cotton. Differences between the declared and the real volumes of traded organic fiber can be significant (Ton, 2007; OE, 2008a).

### **2.2.5. Cotton Harvesting**

Harvesting involves the removal of opened bolls from the cotton plant. Harvesting should be conducted as all harvestable bolls are totally open in order to avoid yield losses (Collins, 2006).

The cotton is picked either manually or mechanically. In low-income countries cotton is mainly picked by hand to maximise the quality and cleanliness of the cotton. Whereas in high-income countries mechanical methods are used (Loursen et al., 1997). About 30% of world production is machines carried out.

Hand picking is a very labour intensive and time-consuming task (UNCTAD, 2002). Although hand-picked cotton has an advantage in marketing, the cost and availability of labor and duration of picking period may necessitate mechanization (Gillham et al., 1995). Cotton is usually mechanically harvested with two types of harvest equipments: spindle pickers and cotton strippers, which pull the fiber from the plant after application of defoliation or desiccation (Ravula et al., 2008). The type and percentage of cotton picking in the major cotton producing countries of the world is given in Table 2.6 (Chaudhry, 1997).

Table 2.6. Percentage of hand and machinery picking in major cotton producing countries (Chaudhry, 1997).

Country	Hand Picking %	Machinery Picking %
China	100	-
USA	-	100
India	100	-
Pakistan	100	-
Brazil	90-95	5-10
Uzbekistan	60-70	30-40
Turkey	100	-
Greece	8	92
Australia	-	100

A large amount of cotton plant residue waste left in the field following harvest. This material is comprised of cotton stalks, leaves, weeds, and along with the upper portion of the taproot (Coates, 2000; White et al., 1996).

2.2.5.1. Harvest Aid Chemicals. The main objectives of the harvest aid chemicals are to increase the rate of leaf loss and desiccation before harvest. Some harvest aid chemicals impact the cotton plant in more than one of these ways. The basic categories of harvest-aid chemicals are include boll openers/conditioners, boll openers/enhancers, defoliant, desiccants, and regrowth inhibitors. The primary goals of applying these chemicals are (UC IPM, 2009):

- to stimulate boll opening and maturation
- to improve harvesting efficiency
- to preserve fiber quality to get maximum economic returns

Mechanical harvesting of cotton is greatly aided by the prior application of harvest-aid chemicals to reduce the foliage either by defoliation or by desiccation. Defoliation and by desiccation is not used where the cotton is hand-picked (Loursen et al., 1997).

## **2.2.6. Ginning**

Cotton ginning operation separates lint fiber from cotton-seed while removing the trash from seed cotton and lint fiber (Proto et al., 2000). Cotton ginning is seasonal operation. It begins with the maturing and harvesting of the cotton crop, and ends when the crop is finished (ICAC, 2001).

Cotton ginning is then performed (most often) by mechanically. The principle of mechanical ginning process is to remove moisture and foreign matter, and to separate cottonseed from raw seed cotton (Proto et al., 2000). A simple gin machine sequence such as a dryer, extractor-feeder and gin stand is required; however, a more extensive machine sequence is required for trashy cotton (ICAC, 2001).

After ginning, the ginned cotton fibers compressed into large bales with a weight of 227 kg, wrapped with a protective covering made of woven polyethylene or polypropylene and sent to spinning mills for processing (Anthony et al., 1994; Boykin, 2005). In order to describe the most important substances deriving from the cotton cycle that begins with cotton ginning, the global biomass balance of these resources is reported in Figure 2.4.

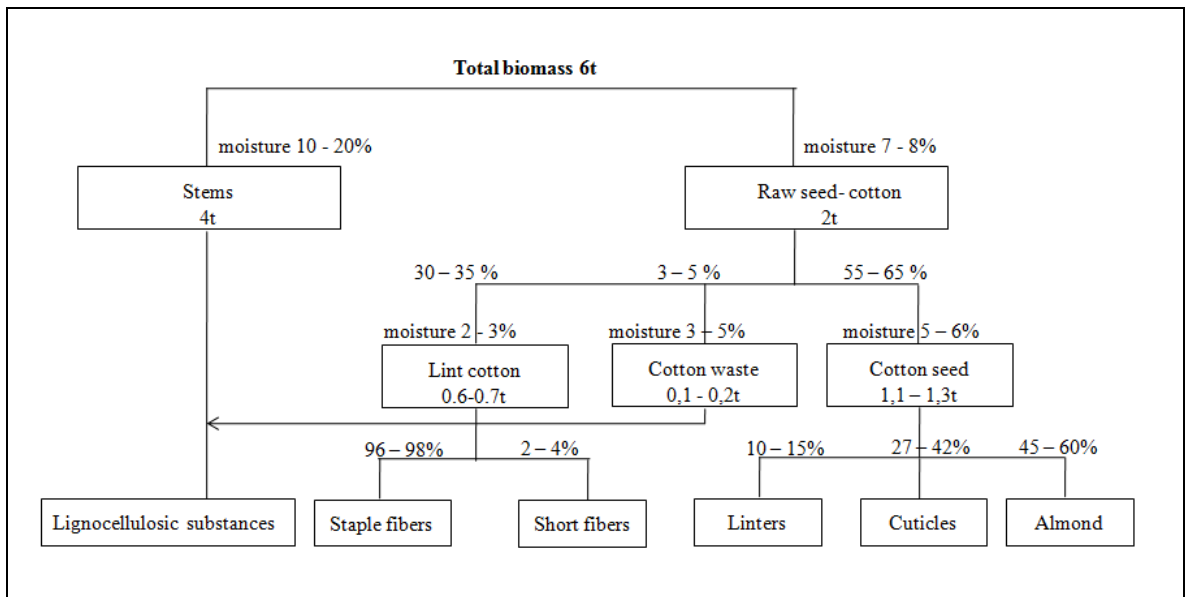


Figure 2.4. Global biomass balance of cotton crop (Proto et al., 2000).

The quality of ginned lint is directly depending on the quality of the cotton before ginning, and proper selection and operation of each machine for fiber quality preservation. (ICAC, 2001). Moisture content is one of the most important factors that influence cleaning performance and fiber damage during processing. Cotton ginning requires a proper moisture content that is not too moist or too dry. Air blowing, the primary method of conveying cotton within a gin, is heated to remove excess moisture from the cotton (Boykin, 2005).

In order to obtain lint cotton, a large percentage of the foreign matter must be removed by two or three stage cleaning. Cotton gin waste consists of sticks, leaves, burs, soil particles, mote, cotton lint, and other plant materials. Slight differences in the proportions of the components are observed depending on harvesting methods employed (Agblevor et al., 2006). Foreign-matter levels in seed-cotton before gin processing usually range from 1% to 5% for hand harvested, from 5% to 10% spindle-harvested, and from 10% to 30% for stripper-harvested cottons (ICAC, 2001).

### **2.2.7. Yarn Spinning (Yarn Production)**

The term "spinning" refers both to the final stage of yarn manufacturing that puts a twist in the yarn, and also to the whole sequence of stages that convert raw fibers into usable yarn. Yarn production from staple fibers involves opening, cleaning, blending, carding, combing, drawing, roving and spinning (Bralla, 2007). The sub-processes used for yarn formation are described below:

In the first stage of yarn manufacturing; compressed cotton bales are subject to blending, opening and cleaning operations respectively (Sen, 2001). Blending of different bales is implemented to provide fiber uniformity and to improve fiber quality. During opening and cleaning stages; closely packed fibers are loosened and unwanted materials such as leaves, twigs, dirt, any remaining seeds etc. are separated from the fibers (Bralla, 2007; Sen, 2001).

In the carding step, brushes of carding machine cause continuance of cleaning, removing some amount of short fibers, fiber individualization, partially aligning the fibers, and disentangling of immature fibers (Sen, 2001). Following to carding, combing operation occurs. It is similar to previous operation except that the brushes are finer and more closely spaced compared to carding machine. The main objectives of the stage are to remove of shorter and unmaturing fibers, and to align to fibers more accurately (U.S.EPA., 1997).

Functions of drawing are to further straighten the fibers, make them parallel and improve the uniformity by doubling (Sen, 2001). Generally, one-two or three repeated operation is used to get required yarn characteristics (Anthony et al., 1994). Roving is the final stage in the spinning preparatory operations is used to stretch the yarn further. So; the weight of material being fed to the spinning frame does not exceed the capability of the frame. Final resultant product is called the roving (Sen, 2001).

Spinning is final phase of yarn manufacturing that roving are twisted together to form yarn. Main principles of system are to extend, thin and twist of roving, and then wind up a bobbin for storage. The three main spinning technologies used on a commercial scale are: ring spinning, rotor (open-end) spinning, and air-jet spinning (Bralla, 2007). The ring

spinning system is the oldest and dominant type of spinning system that allows processing of various types and lengths of fibers. Because of high energy consumption and low production speed, ring spinning is comparatively expensive (Koç et al., 2007).

### **2.2.8. Fabric Formation**

Fabric formation is a process of converting a set of yarns into a fabric. This stage is fully specialized machinery and equipment. The major methods for fabric formation are weaving and knitting (U.S.EPA, 1996). These are described in turn below:

2.2.8.1. Weaving. Weaving is the most common and the oldest method used to create fabrics which yarns are assembled together on a loom and woven fabrics are obtained. The basic principle of weaving is interlacing one set of yarns with another set oriented crosswise (U.S.EPA, 1997).

2.2.8.2. Knitting. The second most frequently used method of fabric formation is knitting (U.S.EPA, 1997). Like weaving, knitting is a purely mechanical process and includes knotting yarn together with a series of needles (EC, 2001). Knitted fabrics are easy to produce compared to woven fabric. Moreover, the popularity of knitted fabric has increased in use due to high extensibility, shape retention on heat setting, crease and wrinkle resistance, pliability, better thermal insulation property and better comfort property (Sen, 2001).

### **2.2.9. Wet fabric processing**

Wet fabric processing improves the appearance, durability and serviceability of fabrics by converting undyed and unfinished goods into finished consumers' goods. It may be grouped into three main stages: fabric preparation (pre-treatment), coloring, and finishing. Some of sub-processes are optional depending on the style of fabric being manufactured (U.S.EPA, 1997).

2.2.9.1. Preparation (Pre-treatment). The main goals in cotton preparation are to remove impurities and modify the fabric for subsequent processing which includes colouring and finishing. Final surface design and certain qualities of fabric for end use are depending

upon success of pre-treatment applications. The preparation of cotton includes a series of sub-processes: desizing, scouring, bleaching and mercerizing (Ren, 2000). The sub-processes of preparation are described below:

1) Desizing:

This stage is carried out on woven fabrics to remove natural sizing materials such as water-insoluble starches, mixtures of starch and other materials from the fabric surface (Aly et al., 2004).

2) Scouring:

Scouring is applied for the removal of non-cellulosic impurities and foreign matter like pectins, waxes, proteins, ashes and others which mostly locating on the outer surface of the cotton fiber. Efficient scouring results in good absorbency or wettability subsequent dyeing and finishing processes (Wang et al., 2007). De-sizing and scouring operations are often combined (U.S.EPA, 1997).

3) Bleaching:

This stage is used to remove unwanted natural colouring matter and/or extraneous substances from fabric by using chemicals. Hydrogen peroxide is the most commonly used bleaching agent for cotton and cotton blends (U.S.EPA, 1997).

4) Mercerizing:

The goals of mercerizing are to enhance to ability to take up dye, to improve tensile strength and to give a silky sheen to fabric (U.S.EPA, 1996).

2.2.9.2. Coloration. Coloration includes dyeing and/or printing which basically involve diffusion of dye molecules into the textile fabric (U.S.EPA, 1997).

### 1) Dyeing:

Dyeing is performed to give a uniform and permanent color to fabric (U.S.EPA, 1996). Environmental performance of process is depending on specific water and energy consumption, dyestuff fixation (%), liquid ratio (LR), heavy metals in dyestuffs, use of environmentally hazardous chemicals, and depth of shade (shading, S%) (Ren, 2000).

### 2) Printing:

Fabrics are often printed with a mono or multi colour patterns using a variety of techniques and machine types. Common printing techniques are rotary screen, direct, discharge, resist, flat screen, and roller printing (U.S.EPA, 1997).

2.2.9.3. Finishing. Applications of mechanical and/or chemical processes in the finishing stage aim to improve quality, visual appearance, texture, or performance (U.S.EPA, 1997).

### 1) Mechanical Finishing:

Mechanical finishing or dry finishing utilizes mainly mechanical means to increase the luster and feel of textiles (Hindler et al., 2004). The well known mechanical finishes are heat setting, brushing, softening, optical finishing, shearing and compacting (U.S.EPA, 1997).

### 2) Chemical Finishing:

Chemical finishing, also referred to as wet finishing involves the addition of chemicals to textiles in order to obtain unchanged physical or chemical properties such as dimensional stability or flame retardancy (Hindler et al., 2004). The most common chemical finishes are optical, permanent-press, soil-release, softeners and stain resistant finishes. Chemical finishes are usually followed by drying, curing, and cooling steps (U.S.EPA, 1997).

2.2.9.4. Wastewater treatment and LCA applications. Wastewater is the largest waste stream for the textile industry. Wet processing operations, including preparation, coloring and finishing, generate large volume of wastewater. The amount of water used varies widely in the industry, depending on the specific processes operated at the plant and the equipment used (EC, 2001).

Wastewater treatment facilities are endowed with a number of risks and different environmental impacts that may inflict some serious damage to its environment. With application of LCA, different wastewater treatment methods and or scenarios based on auxillary consumption, energy consumption used for mechanical installation, sludge generation, greenhouse gases (GHG) could be analyzed and assessed over the entire life cycle of wastewater treatment processes. Moreover, economical aspect of alternative wastewater treatment methods is equally important decision making focus point that could be analyzed with the aid of LCA. In literature several publications were found where LCA have been applied to assess the environmental aspects of different wastewater treatment systems. The differences mainly originated from the various goals and scopes of the researches. According to their scope and system boundaries, different approaches are summarized and compared in below:

Emmerson et al. (1995) studied construction and demolition of wastewater treatment plant than their operation by using LCA. Results showed importance of material and energy use. Biofilters were found to be preferred compared to activated sludge, in spite of a higher material requirement on account of less energy use and less emissions to air.

Another LCA study performed for different conventional wastewater treatment plants. Construction, chemical use, electricity and emission of substances were taken into account in this LCA study. According to the results, chemical pre-treatment was found favorable compared to biological treatment method (Odegaard, 1995).

An investigation is performed by Wilson et al., (2000). Environmental performance and environmental impacts of a wastewater treatment plant were analyzed in this study. Moreover, opportunities to improve its environmental performance were also investigated. The sewage treatment plant was selected in order to analyze energy consumption over its three life cycle stages: construction, operation and demolition. Result of study indicated

that 32.5% and 67.5% of total life cycle energy consumption occurred during construction stage and operation stage respectively. However, demolition phase used a negligible amount of total life cycle energy.

In another LCA is applied to identify the energy consumption of each stage of different technologies in municipal wastewater treatment from the view of whole process. Integrated oxidation ditch was investigated from the point of goal and scope of the study. In this respect, energy consumption from its raw and processed materials exploitation, construction, treatment and running, rebuilding to its discarding and removing were identified, quantified, and evaluated. This study indicated that application of the high-energy-efficiency aeration device and optimizing control operation were essential in order to improve the energy consumption of integrated oxidation ditch during its life cycle (Tan et al., 2007).

Roeleveld et al. (1997) performed an LCA of different conventional wastewater treatment methods in order to assess the total environmental burden of the systems. The study indicated that to improve the sustainability of the systems, minimizing the discharge of emissions from the effluent and minimizing sludge production were focus points of the systems. Energy use, construction and the use of chemicals were considered less important compared to other activities.

Another LCA study of wastewater systems was focused on the consequences of a change in the existing wastewater systems in two Swedish municipalities, and included an analysis of the environmental load of both the construction and the operation of the systems. Two alternatives were compared to the existing conventional systems; a local treatment in sand filter beds and a urine separation system. Changes in the wastewater system that might affect surrounding technical systems were approached through system enlargement (Tillman et al., 1998).

Mels et al. (1999) aimed to identify more sustainable sewage treatment scenarios which rested upon physical and chemical pretreatment evaluating sustainability and costs. In the research, sustainability criteria of energy and chemical consumption and sludge production were evaluated. Results of research indicated that physical-chemical pretreatment leads to energy saving when biological post treatment is applied. Moreover,

more energy can be generated through sludge digestion, due to an increased sludge generation. However, the increased particle removal also led to an increased final sludge production after digestion which will have to be disposed of and to a relatively high consumption of chemicals.

A LCA study performed by Vlaopolous et al. (2006) had considered a process water flow of 10.000 m<sup>3</sup>/day for a time period of 15 years as the functional unit used in order to investigate the environmental impact of 20 technologies suitable for treating extensive volumes of water produced during the oil and gas extraction processes. This study proved that dissolved air flotation, absorbents, dual media filtration and reverse osmosis technologies offer relatively low environmental impact parts of systems for cleaning such process waters.

A LCA comparison of several treatment processes for small and decentralized communities was made by Machado et al. (2006). The study focused on the construction, operation and disassembling phases of natural systems (constructed wetland and slow rate infiltration) and a conventional one (activated sludge). According to the results, the lower environmental impact of natural wastewaters treatment plants was clearly demonstrated mainly resulting from less resource requirements. However, the high energy consumption (22 h/d) is the main responsible for the environmental impact of the Activated sludge treatment during operation and maintenance stages.

Halleux et al. (2006) aimed to compare the situations "with" and "without" wastewater treatment plant. Results of the study revealed the importance of the contributions to the global environmental impact of the production of the electricity and the products consumed by the plant, of the production of the building materials, of the transportation and the incineration of the sludge and finally of the pollutants still present in the treated water in the situation for "with" a wastewater treatment plant. However, the study has also demonstrated that the construction of a wastewater treatment plant was necessary and an improvement of the performances of the plant would be done by reducing concentrations of the polluting substances in the effluent water.

Lim et al. (2009) analyzed to synthesize existing distributed and terminal wastewater treatment plants into an economical total wastewater treatment network system from the perspective of LCC. Cost analyzes were structured around cost contributors of construction, operations and maintenance, and disposal stages. The study was demonstrated that the total wastewater treatment network system had the lowest LCC with a rate of 12%.

#### **2.2.10. Fabrication**

Finished textile product is fabricated into a variety of apparels, households and industrial products by cutting trades. Fabrication is conducted on a manuel or a semi-automated basis (Loursen et al., 1997).

The fabrication consists of a series of operations, each performed by a separate person, using production-type equipment. When textiles are produced in quantity, the same basic sequence of operations is implemented to fabrics. First of all, fabrics are spread on a table in order to produce a multi-layer stack, so as to facilitate cutting. In order to provide a guide for cutting pieces of the proper size, fabrics to be sewn are marked by tracing full-size cardboard or fiberboard patterns on a sheet of paper. After arrangement, cutting the stack of fabric into pieces of suitable size is achieved by cutting equipments like round knife oscillating knife, band knife or press cutting (Bralla, 2007). After cutting room, pieces are sewn together to form final design of textile products. The product may then be steam-pressed to flatten the fabric and create crisp edges (U.S.EPA, 1997).

Cutting introduces a remnant of textile. Numerous factors affect the amount of fabric remnant generated in these series of operations, including pattern layout efficiency, the level of expertise of cutting and sewing operators and the complexity of the product e. g. bed linen, trousers and shirts (Weidema et al., 2003; U.S.EPA, 1996).

#### **2.2.11. Use**

Cotton fibers is inherently strong, and it is stronger when wet than it is when dry. This property, allied with cotton's stability in water and alkaline solutions, endows cotton textiles with a long useful lifetime (Cook, 1968). Although it is very difficult to quantify

the exact durability of textile, cotton textiles can withstand repeated washings and can be laundered time and time again (Loursen et al., 1997).

The resistance of cotton to washing and wearing is matched by the permanence of many cotton dyes and also finishing operations, either mechanical or chemical. Colors often remain fast to repeated washings and prolonged wear. In addition to these excellent properties, cotton cellulose is not affected unduly by moderate heat, so that cotton textiles can be ironed with a hot iron without damage (Cook, 1968; Ren, 2000).

There are some environmental impacts in the manufacture and delivery phases of clothes, washing machines, dryers, irons and detergents, as well as in the consumption phase (Jarvi et al., 2007). Although, customers are a critical driver for greater sustainability, the most significant environmental impacts are often resulted from consumer behavior during the use phase of textiles (Weidema et al., 2003). Economic realities and social rules of cleanliness require that textiles be cleaned and refurbished for reuse without substantially altering their functional and aesthetic properties. Thus, increasing demand on cleanliness lead to an increase the consumption of energy, water and detergents (Wentz, 1996; Jarvi et al., 2007).

#### **2.2.12. Disposal**

Textile wastes generate either from post-consumer or pre-consumer. Post-consumer textile waste includes any type of garments or household textile waste that the owner no longer needs and decides to dispose. Pre-consumer textile waste includes by-products from the textile, fiber and cotton industries and they are recycled into new raw materials for the automotive, furniture, mattress, coarse yarn, home furnishings, paper and other industries. However, post-consumer textile wastes are usually disposed of into the trash and end up in municipal landfills (CTR, 1997). Of all the used textiles gathered separately, only one-half are reused (e.g. in second hand). Textiles, for which there is no possibility of reuse, can be recycled on the material level if they consist of homogenous or separable fiber. The main environmental impacts of the disposal are the requirement for landfill space, emissions generating from incineration or deposition, and the environmental and developmental impacts of trading used clothes (Seuring, 2004).

### 3. COMPARISON OF CONVENTIONAL AND ECO T-SHIRT THROUGH LCA; AN ENVIRONMENTALLY DECISION MAKING TOOL

#### 3.1. Goal and Scope Definition

The goal of the study is to identify and to compare all the determinable environmental impacts for conventional T-shirt and three different variants of ECO T-shirt which supply the same functional specification. Potential environmental impacts are assessed for selected cotton T-shirts. In order to achieve this goal GaBi4 software tool is used and to fulfill the complete life cycle impact assessment EDIP2003 methodology is carried out by GaBi4.

All relevant inputs and outputs in the LCI phase and final impact scores generated in LCIA phase are expressed with a reference flow, which is called functional unit. In order to represent the outputs of the study, functional unit is determined for a life cycle of 1000 items of knitted and dyed cotton T-shirt with a total weight of 200 kg, each T-shirt having 200g. Four different life cycle analyses were carried out for T-shirts (Table 3.1). The scenarios were developed based on changes in raw material selection, agricultural productivity of raw material and means of wet fabric processing. For each scenario, environmental impacts of products were assessed through life cycle perspective.

Table 3.1. Side by side comparison of life cycle scenarios.

<b>Scenario</b>	<b>A</b>	<b>B</b>	<b>C</b>	<b>D</b>
Function	Conventional T-shirt	ECO T-shirt	ECO T-shirt	ECO T-shirt
Weight (kg)	0.2	0.2	0.2	0.2
Pieces	1000	1000	1000	1000
Total mass loss (%)	25.93	25.93	25.93	25.93
Raw material	Conventional cotton	Organic cotton	Organic cotton	Organic cotton
Cultivation productivity (%)	100	100	75	50
Wet processing	Conventional bleaching	Green dyeing recipe	Green dyeing recipe	Green dyeing recipe

For both of the conventional and ECO T-shirt, the following steps of life cycle stages as shown in Figure 3.1 have been included in the study:

- cotton fiber cultivation and harvesting
- transport of seed-cotton
- cotton ginning
- yarn production
- transport of yarn
- fabric formation (knitting)
- wet fabric processing
- T-shirt making up
- T-shirt use
- transport of used T-shirt to incineration plant/incineration

The system boundaries are summarized as follows:

- for raw material acquisition; organic cotton growth and evaluation of organic farming productivity are determined as one of the main audit focus points
- for dye-house applications; priority is given to chemical substitution and reduction
- for the service stage; a life time of 3 years that covers 50 times washing at a temperature of 60 °C is selected
- secondary products such as cotton-seed, fabric scraps are not taken into account in terms of neither on-site recycling nor industrial symbiosis
- for transportation placed in boundary; transport only among from farm to ginning plant, from yarn manufacturer to knitting house and from transfer station to incineration plant are considered

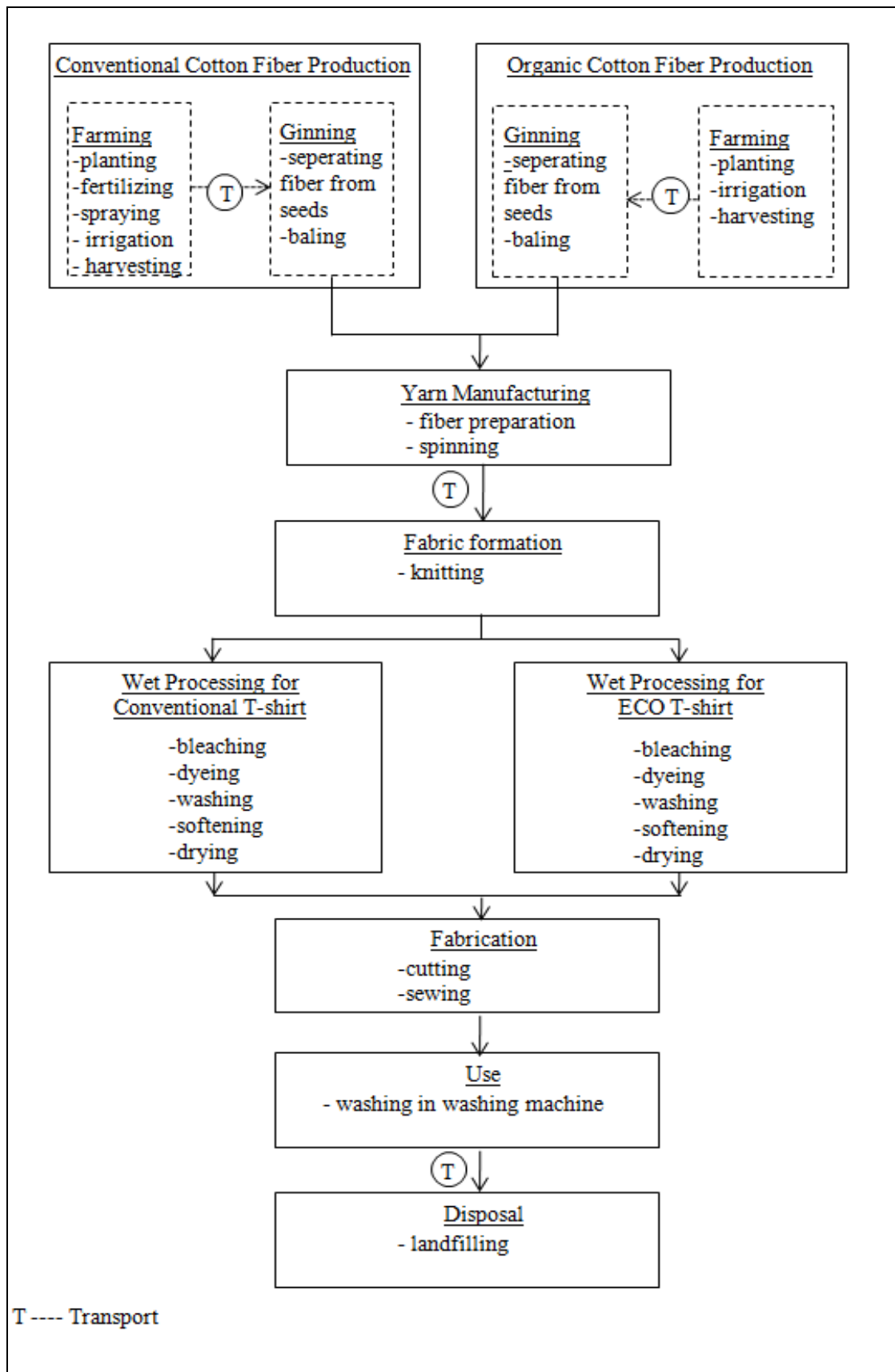


Figure 3.1. Investigated and compared life cycle system boundaries.

### 3.2. Inventory

At the inventory phase; complete input and output analyses have been carried out for all life cycle stages of T-shirt. In order to assess the life cycle impact of each process in the scope, plans for each stage and integration of processes within the related plan, a sub-process of whole production plan have been realized. Balances in GaBi4 are calculated based on individual or multiple processes and plans. The inventory data related to system boundary are aggregated from GaBi4, scientific papers and research reports. For wet fabric processing, a dyehouse, located in Hadımköy, Istanbul provided site-specific and process data.

As 25.93% amount of cotton/fabric is considered to be lost during its overall life cycle. 270.02 kg of raw cotton (lint) fiber is required to produce 1000 items of cotton T-shirt with a total weight of 200 kg. Figures 3.2 represents mass losses during life cycle of Conventional T-shirt.

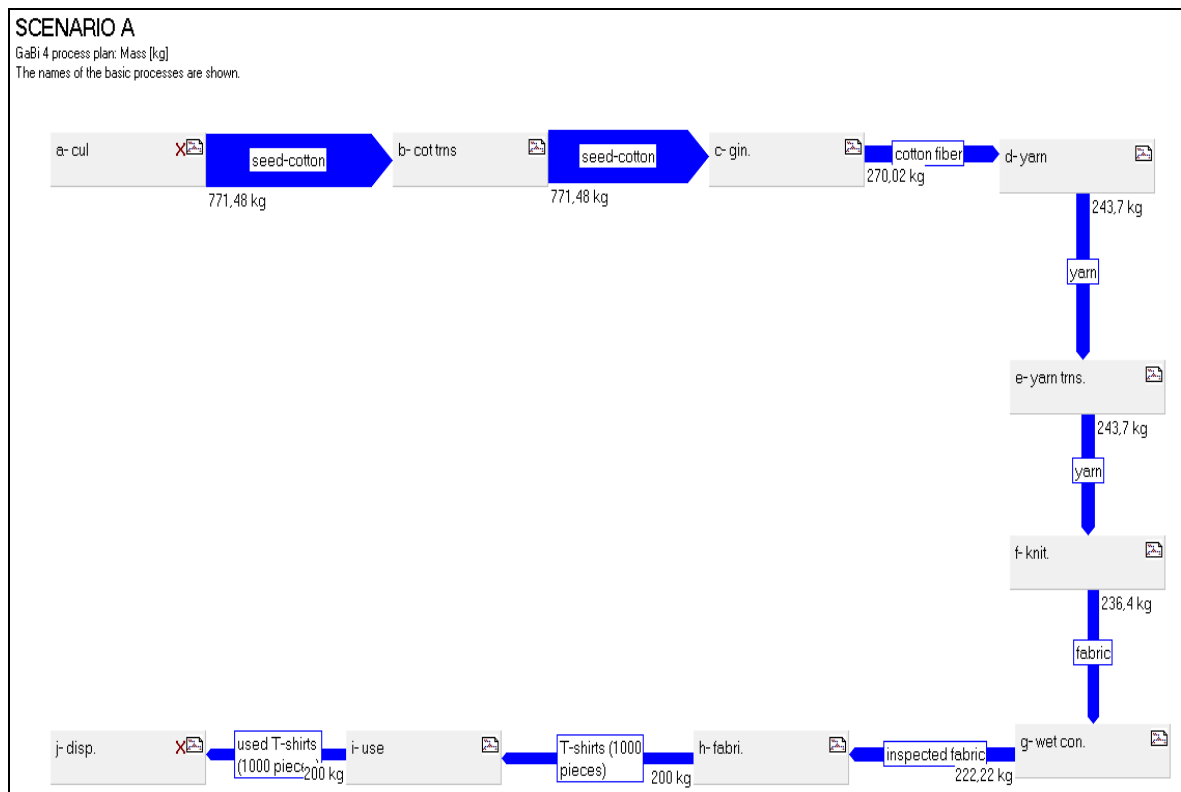


Figure 3.2. Mass view of conventional T-shirt life cycle.

Energy consumption at each step of processing of cotton to produce T-shirt is associated with fuel and electricity consumption of various types of machines in production processes and chemicals consumption.

In the light of LCA methodology, the input and output data in LCI were inserted into the GaBi4 software to calculate emissions taking functional unit as baseline. The input/output data of LCI were linked to relevant libraries in GaBi4. The LCA library is a database that consists of energy consumption, emission and materials data for the production of 1 unit of a product. The units of input and output data of LCI depend upon the units of the relevant materials like kg, L, MJ etc. in GaBi4 software. A Sankey diagram is developed, allowing a quick overview of mass, energy or even cost flows shown as proportional to quantity in order to assess product related environmental effects.

As described in system boundary, overall life cycle stages for conventional and ECO T-shirt variants are similar. The differences are observed in cotton cultivation and wet fabric processing applications. Complete mass and energy balances from raw material acquisition to disposal of final product for the two selected products are given below:

### **3.2.1. Conventional Cotton Cultivation**

The fiber production data utilized in the LCI calculations of this study is surveyed mainly on the basis of literature information from several sources in order to enable cross-checking of data, applied specially for cotton production references. It should be noted that crop productivity, types, and application rates and values of fertilizer and pesticides vary a lot from country to country, from one region of a country to another and even from one field of a region to another. So, world averages, a country or a region can be selected for which the data is applied to develop a LCI. Lack of data in several areas makes it practically impossible to obtain reasonable, applicable and reliable data averages for all data types. To overcome this barrier and ease the analysis, input/output values and decision making points are defined according to selected reference area: Antalya/ Turkey. Apart from data representing this region, evaluated sources and multi-dimensional decision making points that form the inventory part of cultivation stages are discussed below:

In 2004 (Canakci et al., 2005; Yilmaz et al., 2005), the average crop yield in Antalya was investigated as 3100 kg seed-cotton/ ha (approximately 1100 kg-lint/ha). This yield also depends that modern agriculture methods are used at this part of Turkey. In this study, diesel is consumed in the machinery operations. Consumption of diesel is estimated once the farming operations and established for the crop production (Canakci et al., 2005; Yilmaz et al., 2005).

There are many differences for fertilizer application rate and frequency in the literature due to soil characteristics (Chapagain et al., 2006). For this reason, application rates of fertilizers are estimated by evaluating different representative sources. Studies performed in Antalya supported excessive nitrogen fertilizer consumption in the research region (Canakci et al., 2005; Yilmaz et al., 2005). Along with fertilizer consumption, this study also takes into consideration other potentially important environmental factors; such as emissions of ammonia, nitrate, nitrous oxide and phosphate emissions which arise in varying quantities. Background data on emissions generating from N and P fertilizer application are quantified by using methods to estimate on-field nitrogen emissions (Brentrup et al., 2000).

As for other chemicals, such as pesticides, insecticides and fungicides, there are countless different agents to protect cotton against insect attacks, weeds and fungus. It is decided to implement a representative chemical from each of the three main categories insecticides, herbicides and fungicides. Application of growth enhancers and defoliation agents are not common in Turkey (Kooistra, et al., 2006). It is difficult to evaluate the dosage of chemicals. Cotton may be attacked by many different kinds of insect, many different types of weed and fungus. So, several types of chemical may be used for several times to protect crop. The total dose of the chemicals changes between 1.85 kg/ha and 10.5 kg/ha (Canakci et al., 2005; Yilmaz et al., 2005). Figure 3.3 taken from GaBi4 program illustrates developed sankey diagram for conventional cotton cultivation.

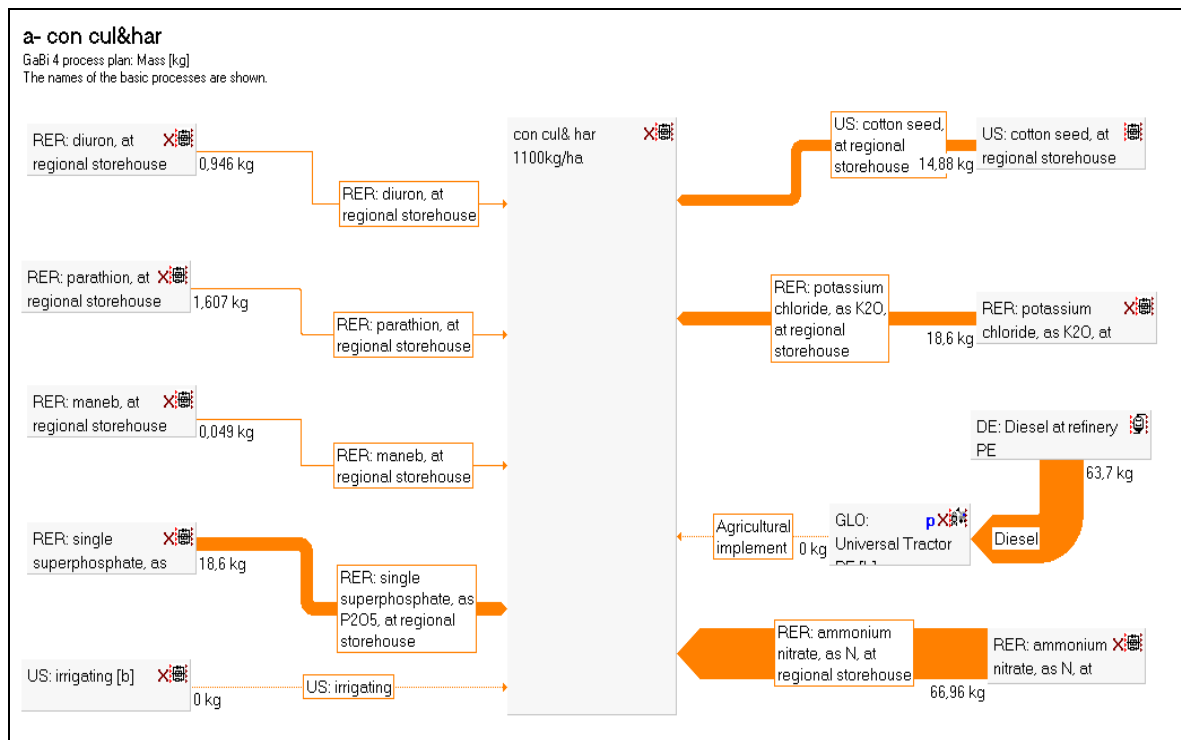


Figure 3.3. Sankey diagram from GaBi4 for conventional cotton cultivation and harvesting.

### 3.2.2. Organic Cotton Cultivation

There are information gaps about organic cotton crop yield in Turkey, where different production totals are reported. Detailed information about organic cropping systems in Turkey is not yet available (Kooistra et al., 2006; OE, 2007; OE, 2006). With respect to developed scenario three different yield productivity for organic cotton cultivation are accepted: for transition period it is assumed that production rate is half of later years (550 kg/lint-ha), after transition it is equal to 750 kg/lint-ha and finally average crop yield for organic cotton cultivation is same with conventional production rate (1100 kg/lint-ha).

In fiber production step, it is important to take into account the influence of agricultural field activities as well as fertilizers and pesticides production and their applications. In order to estimate the energy requirement for production of 1 kg of organic cotton fiber, once it is needed to calculate the energy consumption for production of fertilizer and pesticides in separate processes. Therefore, the amount of diesel to be consumed for application fertilizer and pesticides on agricultural yield has been considered

as another vital factor for determining energy consumption. Subtraction of aforementioned calculation values from energy use in conventional production represents the amounts of energy used for organic cultivation.

Since organic cotton growing requires an upgraded system of farming where soil management is one of the highest priorities, it is assumed that fertilizers based on natural origin used to maintain soil fertility. In order to provide efficient N, P and K, composting, rock phosphate and muriate of potash are used in place of synthetic fertilizers (UNSDAC, 2002; Loursen et al., 1997; OE, 2008b).

Certification systems ban use of toxic pesticides against insect attacks, weeds and diseases (ICAC, 1994). In this LCA, it is assumed that no agro chemicals are used in the production of organic cotton. It is also assumed that no alternative chemicals are used. Pest, weed and disease management is achieved through crop rotation. Finally, irrigation water consumption for organic cultivation is assumed to be same with conventional cotton water requirement.

### **3.2.3. Harvesting**

Harvesting is removal of opened and matured bolls (raw seed-cotton) from the cotton plant and it can be done by mechanically or manually. In this study, it is assumed that cotton is picked by hand in Turkey (Chaudhry, 1997; Yılmaz et al., 2005). In order to achieve leaf loss without using any defoliant chemicals before harvesting, it is assumed that irrigation is effectively managed. So that, the leaves cut out in time to dry up and fall of before picking naturally.

### **3.2.4. Transportation of Seed-Cotton**

After harvesting, the seed-cotton (unginned cotton) is transported from farm to gin as shown in Figures 3.1 and 3.2. Time parameter is not considered for the pathway because, the emissions are calculated with the help of emission factors which only depend on kg of mass carried and distance. The inventory data for seed-cotton transportation is calculated

based on average distance of 100 km traveled by diesel engine equipped truck with a capacity of 12.4t.

### 3.2.5. Ginning

Cotton ginning and it acts as a bridge between agricultural cotton production and textile manufacturing. In the context of the study regarding the Figure 2.4 (Proto et al., 2000), it is assumed that total biomass of harvested seed-cotton is converted to cotton lint, cotton seed and ginning waste by a share of 35%, 62% and 3% respectively. Electrical energy requirement among gins usually range from 40-60 kWh/bale and in order to protect lint, bale is covered with polyethylene film (Anthony et al., 1994).

### 3.2.6. Yarn Spinning (Yarn Manufacturing)

Conversion of cotton fibers to yarn, consists of several sub-stages as illustrated in Figure 3.4. During conversion of fibers to yarn, energy consumption and waste production are taken into account to determine the stage related environmental impacts.

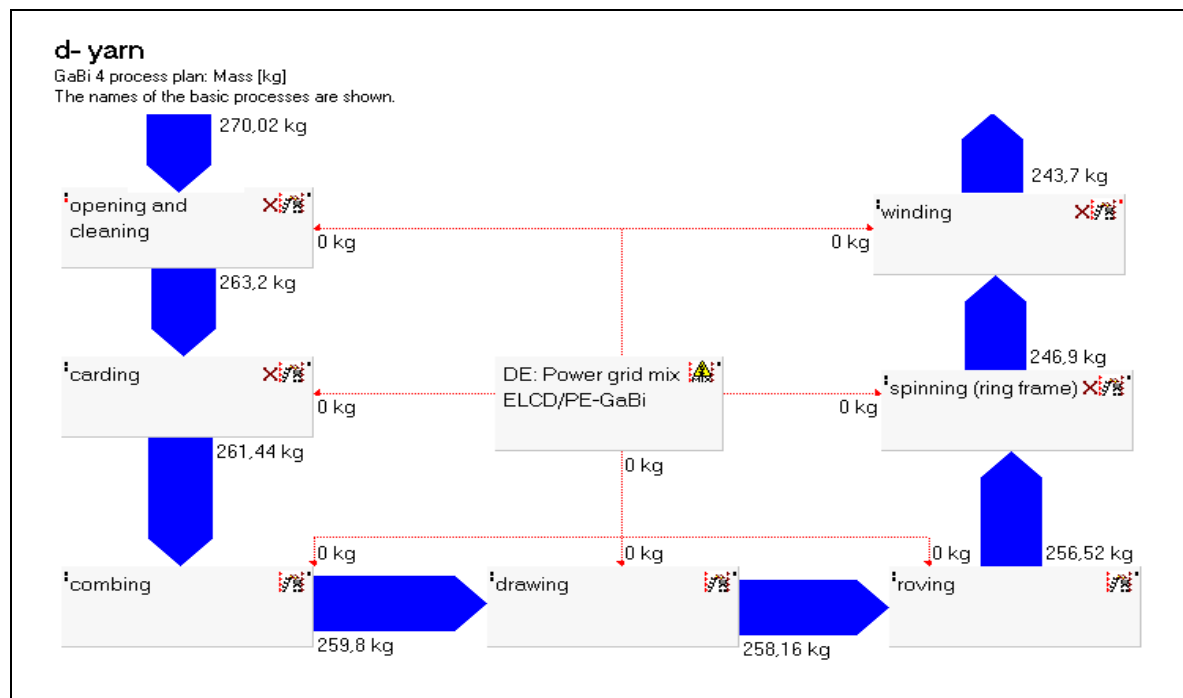


Figure 3.4. Sub-stages and mass losses during yarn-manufacturing.

Literature reveals reliable and a wide range of energy consumption values for yarn production. The energy consumption values according to sub-stages of yarn production are presented and compared in Table 3.2.

Table 3.2. Energy consumption for yarn spinning.

Stages	Sub-stages	Energy consumption ( MJ/ kg yarn)		
		I (Loursen at al., 1997)	II (BTTG, 1999b)	III (Koç at al., 2007)
Preparation	Opening and cleaning	0.72-0.92	2.1	0.243
	Carding	0.58-0.96	2.6	1.847
	Blending and combing	0.48	-	0.751
	Drawing	0.21-0.32	3.1	0.549
	Roving	0.86-1.16	0.8	0.436
Spinning	Spinning	2.16-10.2	18.7	5.635
	Winding	0.76-2.00	5.8	0.690
	Air conditioning and lighting	0.53-2.36	-	2.699
TOTAL		6.33-18.36	33.1	12.850

According to a recent study performed in Turkey, process energy consumption changes between 11.62–13.53 MJ/kg (Koç et al., 2007). For this study, it is assumed that the energy consumption is 12.85 MJ/kg yarn.

Yarn production generates large amounts of residual waste in the form of non-lint trash, fiber waste, sliver, sweeps and dust (U.S.EPA, 1997). The range in total mass loss for yarn formation processes, opening and cleaning, carding, blending and combing, drawing, and roving is about 2-10% and for spinning and winding is about 1-20% (BTTG, 1999a). In this LCA study, accepted mass loss quantities are 5% for preparation and %5 for

spinning. Estimates for the material losses in the form of a solid waste, at different sub-stages of yarn manufacturing can be also seen in Figure 3.4 taken in GaBi4 software.

### **3.2.7. Transportation of Yarn**

It has been assumed that fabric production is performed in Istanbul. So, the average distance between yarn mill and knitting house is considered as 750 km. Energy consumption and related emissions for the transportation of 243.70 kg yarn by diesel engine equipped truck with a capacity of 22t from Antalya to İstanbul are analyzed for GaBi4.

### **3.2.8. Knitting**

In order to evaluate the stage related environmental aspects, the use of electricity for knitting machines and material losses generated during the process are investigated. Data based on literature survey is considerably limited. The textile wastes generated by this operation changes between 2-6% and the range in the energy consumption is about 5-20 MJ/kg textile (BTTG, 1999a; BTTG, 1999b). Within the frame of this study, it has been assumed that the energy consumption is about 5 MJ/ kg and material loss is 3% on average.

### **3.2.9. Wet fabric processing**

The interest of the top management for the selected textile plant located in Hadımköy, İstanbul was supplied for the application of CP. The commitment of the enterprise was achieved for chemical elimination in wet fabric processing. For this reason the audit focus points of were determined for chemical reduction in the dye-house and results are evaluated through environmental performance indicators (EPI) which is specified and expressed by using specific chemical consumption (kg/kg textile), specific water consumption (L/kg textile) and specific energy consumption (MJ/kg textile).

Prior to that, a site visit was carried out in the production plant in order to get related information for CP option generation in the dye-house. The plant has 40.000m<sup>2</sup> outdoor

and 30.000m<sup>2</sup> indoor area. It supplies sub-contractor service with 40 tonnes/day capacity dye house. Cotton fabric dyeing is the main operation of the plant rather than dyeing of other products such as viscose, velvet, polar, polyamide, PES, bamboo, soy, mineral, organic, milk fabrics. The plant operates 24 hours a day, 300 days a year. The company performs bleaching, dyeing, washing, softening and drying operations respectively. Selection of products and determination of production schemes are mainly driven by market demands.

For the dye-house, raw water which is extracted from well, is softened to produce process water. In the plant, the major energy source is natural gas and electricity. In addition to these sources, steam is also a vital source required in the production processes. Natural gas is used for steam production in boilers.

The recipes applied to conventional T-shirt and ECO T-shirt show variations from the point of auxiliary substitution, water and energy consumption. As part of inventory phase, the major goal is to assess water, energy and chemical consumption performances during wet fabric processing with the intent to conduct material and energy balance. A detailed input- output data analyses for the selected recipe of conventional T-shirt will lead to generate CP options. The feasibility considering environmental and economic aspects are considered for the final determination of the “green dyeing recipe”.

For the selected production plant, wet processing of knitted cotton fabric in dye-house is carried out in jet dyeing machine. The processes for both products can be classified as bleaching, dyeing, washing and softening. From the point of water consumption the dyeing process is applied with 1:10 liquor ratio. Figures 3.5 and 3.6 represent the material and energy balances for the selected T-shirt. As it can be seen from the figures shortening of process cycles in order to reduce the specific water consumption and correspondingly energy consumption is an important point of CP. Reduction affects not only the consumption of water but also the consumption of steam for heating up (up to temperature 95°C) the process baths and electricity for machinery driving. As it becomes obvious from the specific water consumption data presented in Table 3.3, filling-draining performed in bleaching and washing units play the most important role in consumption of water and energy between two implemented recipes.

From the selected recipe details, it can be concluded that bleaching is one of the highest water consuming unit operation process that also increases the pollutant load of wastewater treatment plant. Bleaching process implemented for conventional T-shirt production consists of five cycles of water filling-draining that represents nearly 50% of total wet processing time and also water consumption represents one third of the total consumption. In addition to bleaching, washing represents nearly sixty percent of total water consumption which also stands as a main source of water consumption and wastewater generation. It is obvious that improvements through chemical elimination and substitution for bleaching and washing unit operations of dyeing process will lead to “green dyeing recipe” application.

Hydrogen peroxide ( $H_2O_2$ ) bleaching in conventional T-shirt production is the first step for realization of chemical substitution. The method is identified as water and energy intensive. In this sense, reducing agent of sodium thiosulfate ( $Na_2S_2O_3$ ) is consumed to rinse off hydrogen peroxide ( $H_2O_2$ ) prior to dyeing. Moreover  $H_2O_2$  collaborates caustic ( $NaOH$ ) to obtain alkaline conditions, a stabilizer for stable degradation of  $H_2O_2$  and also sequestering agent to prevent insolubilization caused by calcium and magnesium. In addition to that, wetting agent is used to give homogeneous hydrophilicity to the fabric and antipilling agent is used to degrade starch size on cotton fabric.

Regarding bleaching process for ECO T-shirt production; acedic acid, wetting agent and antipilling agent are applied in a series of two processes. For green dyeing recipe, substitution of wetting agent which is combine form of wetting agent, oil remover and antipilling agent is carried out. As summarized in Table 3.3, elimination of  $H_2O_2$  in the bleaching for ECO T-shirt production is resulted in 60% water saving and 61.5% energy savings.

Taking into account washing stage; acedic acid and soap are used in both cases. Regarding dyeing with reactive dyestuff, washing stage necessitates a number of rising cycles to remove of unreacted and hydrolyzed dyestuff from the fabric. Washing stage applied for conventional T-shirt production is performed with the aid of eight cycle water filling-draining. Soap substitution in washing eliminates three water filling-draining resulted in 38% energy and 37.5% water saving during measurements.

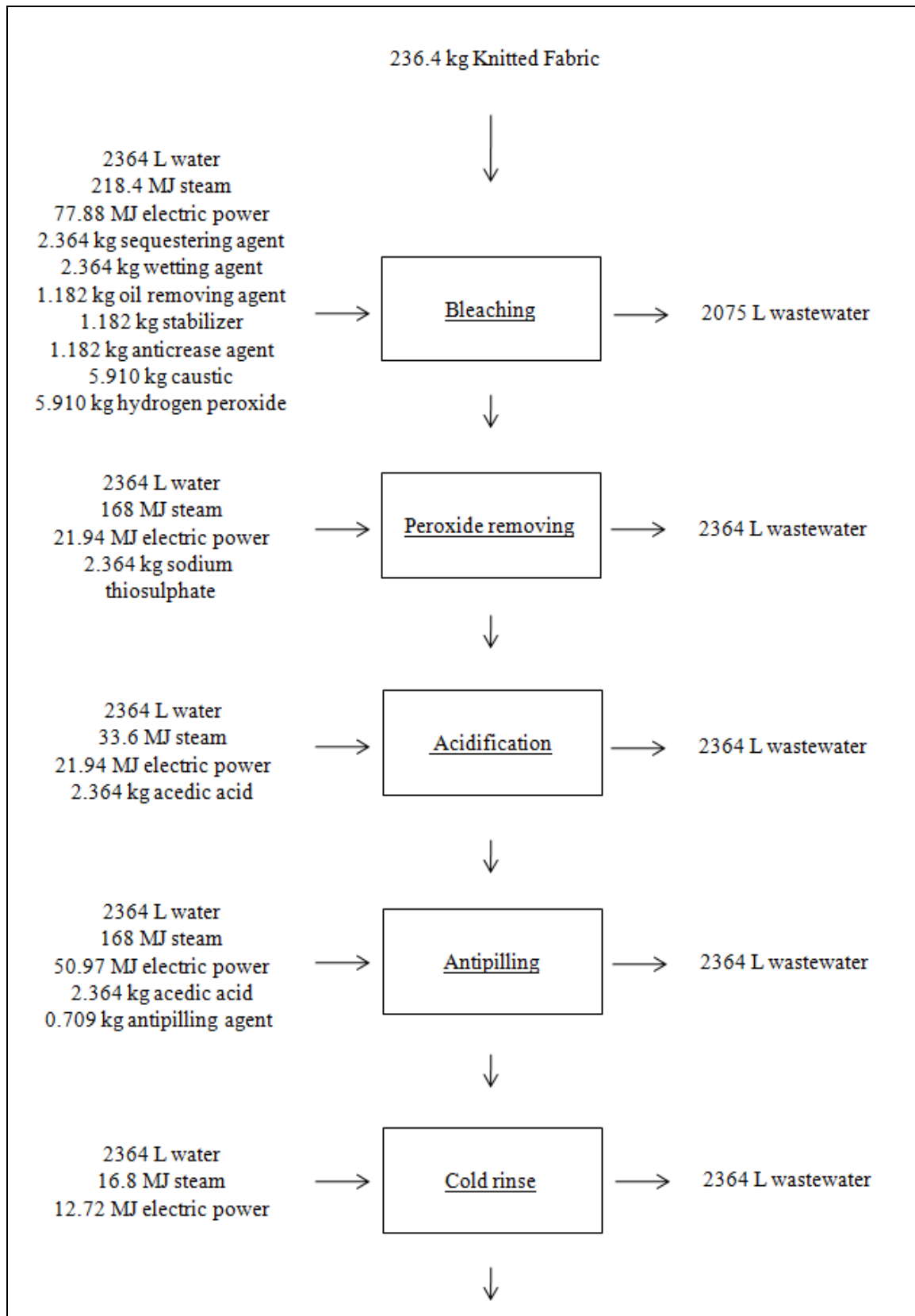


Figure 3.5. Conventional bleaching dyeing recipe for conventional T-shirt (continued on the next page).

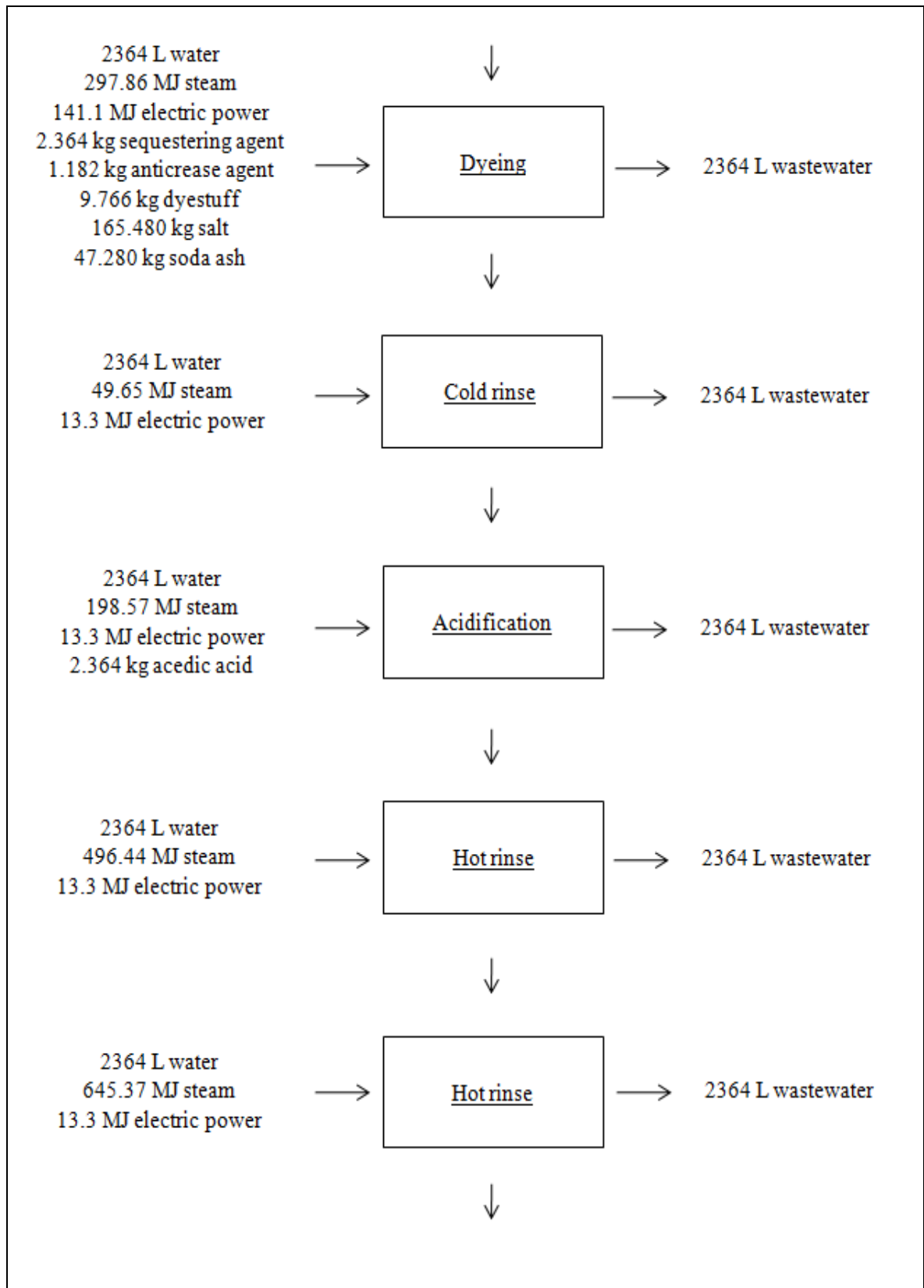


Figure 3.5. (Continued).

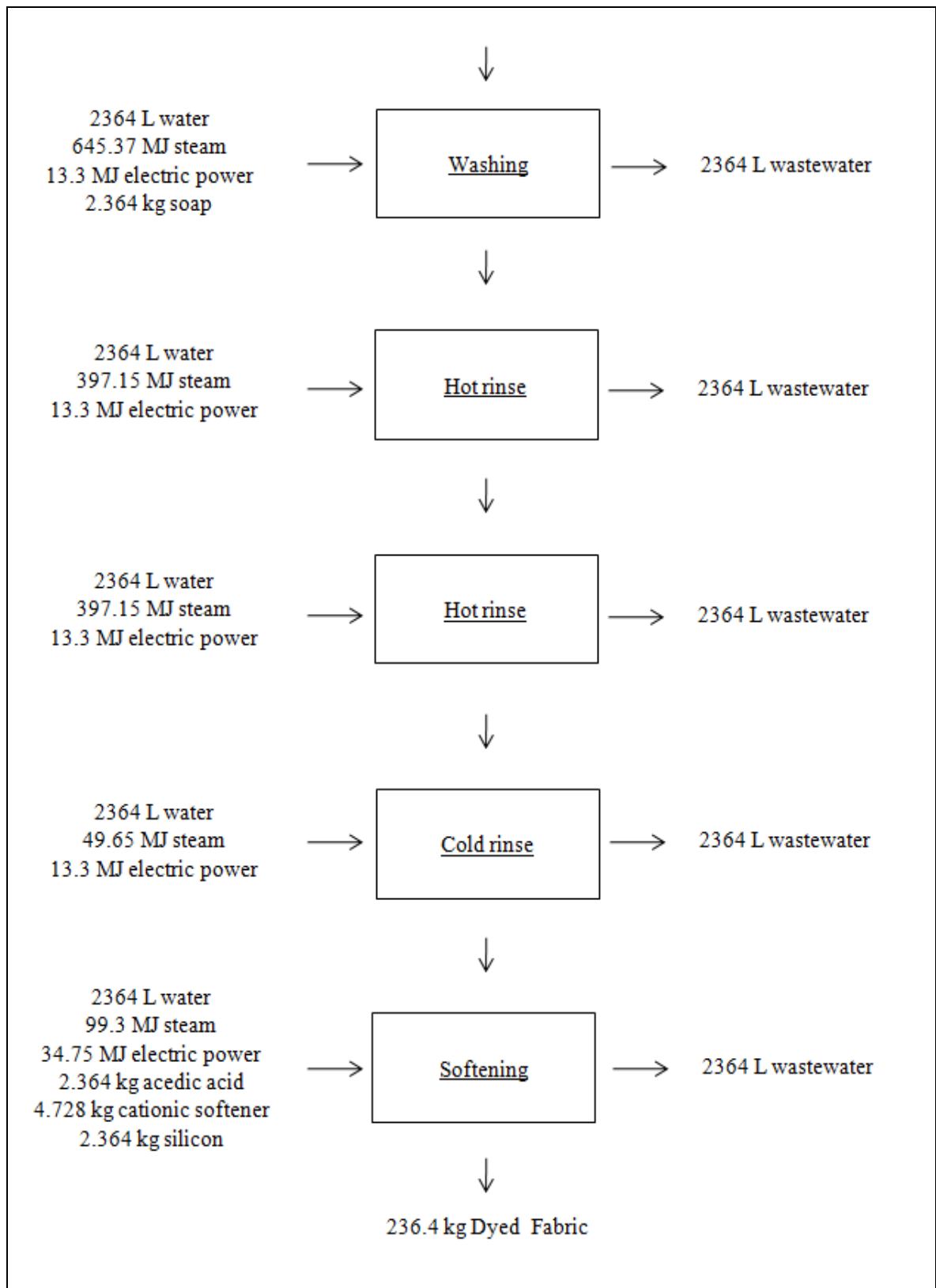


Figure 3.5. (Continued).

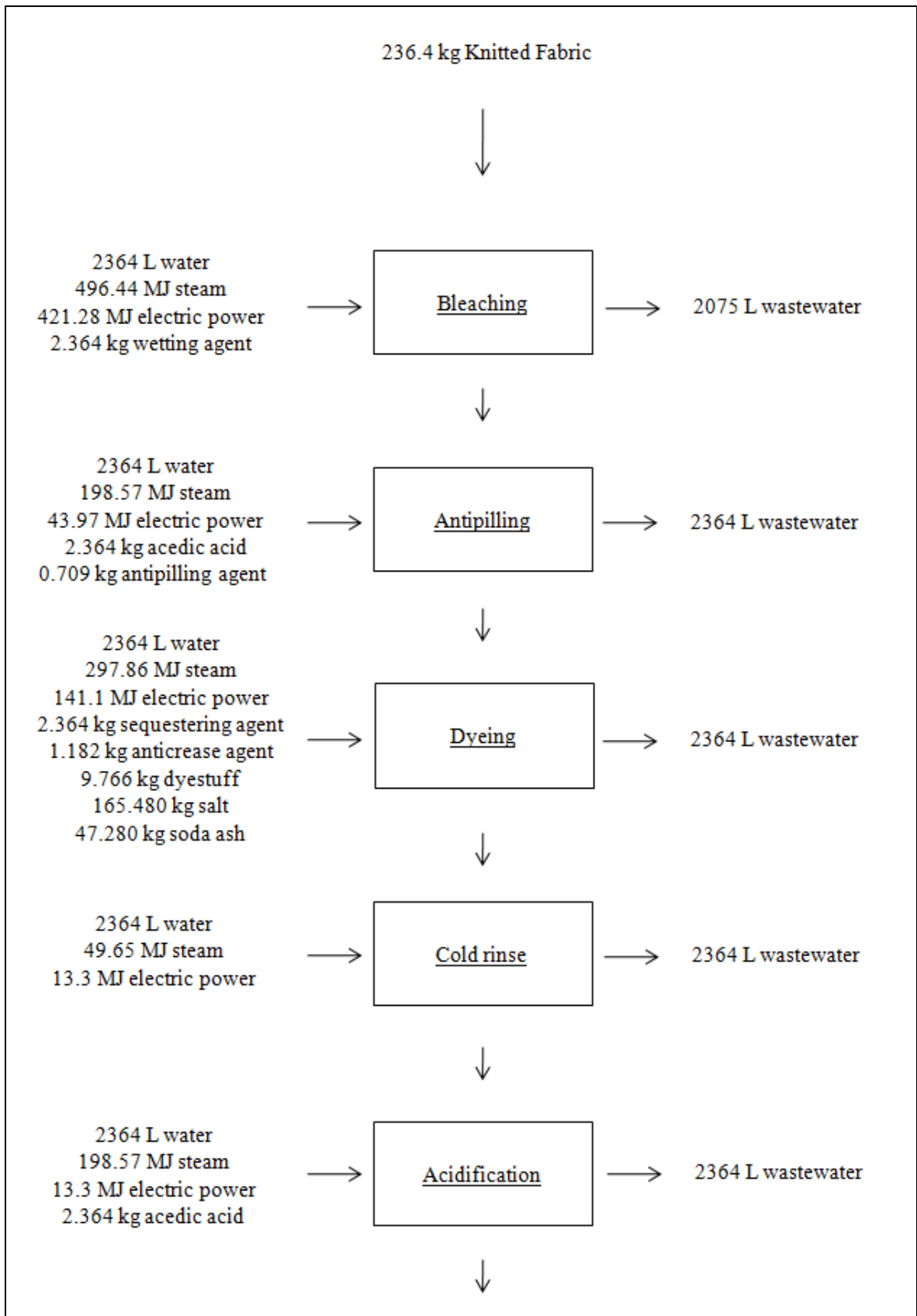


Figure 3.6. Green dyeing recipe for ECO T-shirt (continued on the next page).

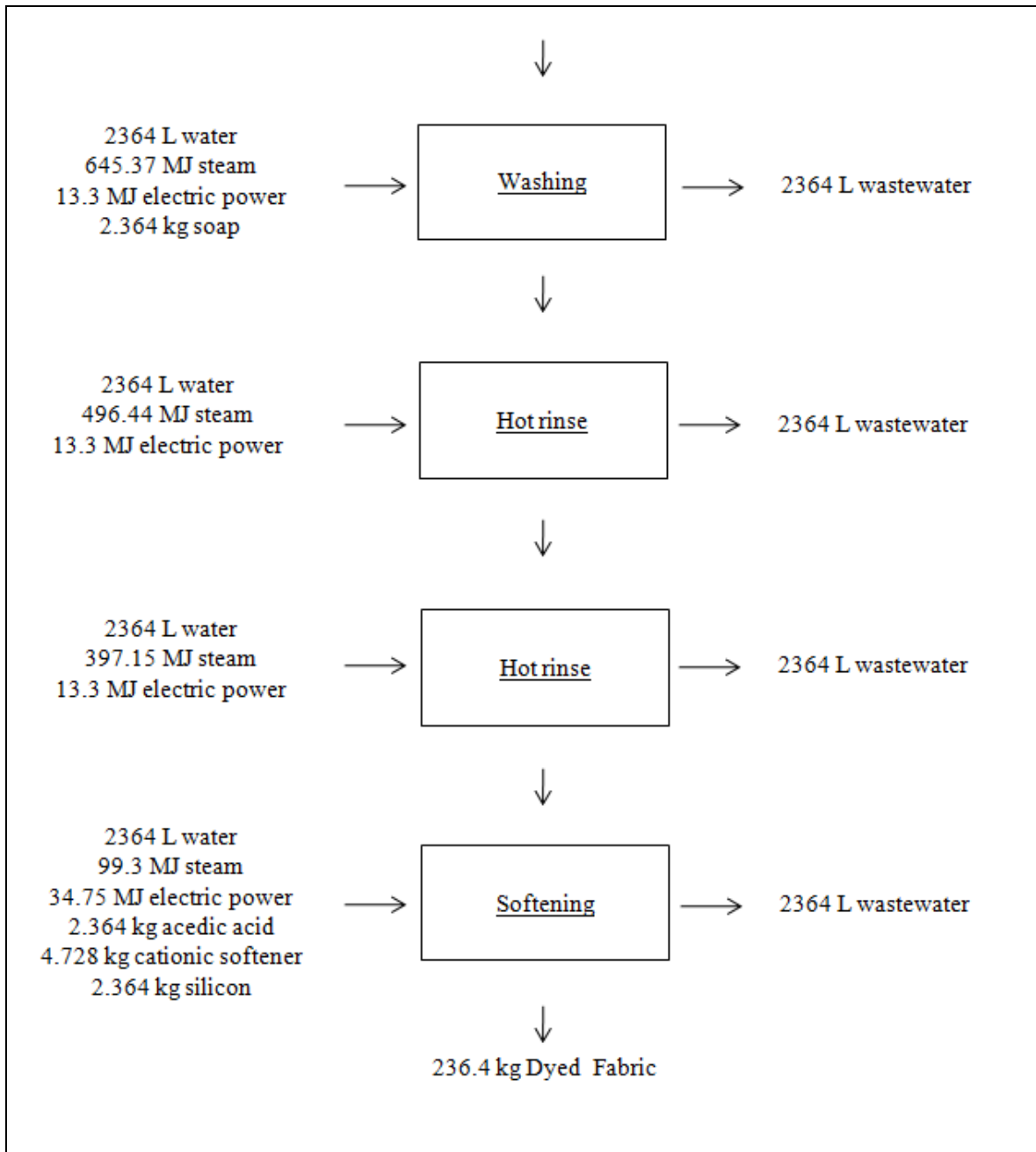


Figure 3.6. (Continued).

Apart from bleaching and washing processes, dyeing, softening and drying operations that are applied for the two recipes are similar. From the point of EPIs, the comparison of a conventional and ECO T-shirt production are as summarized in Table 3.3. Results reflect the performance as well as the improvement potentials.

Table 3.3. Comparison of EPIs for conventional and ECO T-shirt.

Process	Sub-process	Chemical consumption (kg/kg textile)		Energy consumption (MJ/kg textile)		Water consumption (L/kg textile)	
		I	II	I	II	I	II
Preparation	Bleaching	0.118	0.023	8.34	3.21	50	20
Coloration	Dyeing	0.95	0.95	1.86	1.86	10	10
	Washing	0.02	0.02	12.63	7.84	80	50
Finishing	Softening	0.04	0.04	0.57	0.57	10	10
	Drying	-	-	1.80	1.80	-	-
Total		1.128	1.033	25.20	15.28	150	90

I: Consumption for conventional T-shirt; II: Consumption for ECO T-shirt

As it can be seen from Table 3.3, total specific water consumption is reduced from 150 to 90 L/kg. Taking into account energy consumption, 39.5% of energy saving has already been observed. This overall reduction is achieved by the implementation of bleaching and washing operation modifications through chemical substitution. Moreover, the total dyeing process time for ECO T-shirt production will be around 3.5 hours shorter than conventional T-shirt which will approximately being a time saving of 32% from the overall dyeing process duration.

The effluent generated from overall dyeing process is characterized using chemical oxygen demand (COD) value. The wastewater characterization analyses are carried out at Boğaziçi University, Institute of Environmental Sciences. Results indicated that conventional bleaching dyeing recipe performed for conventional T-shirt production has a COD value of 1299 mg/L (46.06 kg). However, green dyeing recipe for ECO T-shirt production has a COD value of 1821 mg/L (38.74 kg) which demonstrates environmental advantages of chemical substitution. Selected indicators are used to develop and compare a sensitive wet fabric processing modeling in GaBi4; LCA tool. Developed sankey diagrams for both recipes are illustrated in Figures 3.7 and 3.8.





In order to fulfill the efficiency of wastewater management system in the LCA methodology, the majority of the LCA applications have been proposed for use at country or region levels. For this thesis, wastewater composition representing an average outflow of EU-27 boundary conditions to the treatment plant with organic and inorganic substances is selected which is also applicable for wastewater of an textile production site (Brauner, 2010). The process steps are taking average elimination and transfer coefficients into account. With the aid of existing information of the selected wastewater treatment system, it was aimed to analyze the environmental aspects and environmental impacts potential associated with the selected wastewater treatment plant and to identify impact categories of wastewater treatment plant which are major contributors to environmental impacts. The background of wastewater treatment process is addressed to outlined conditions as follows (Brauner,2010):

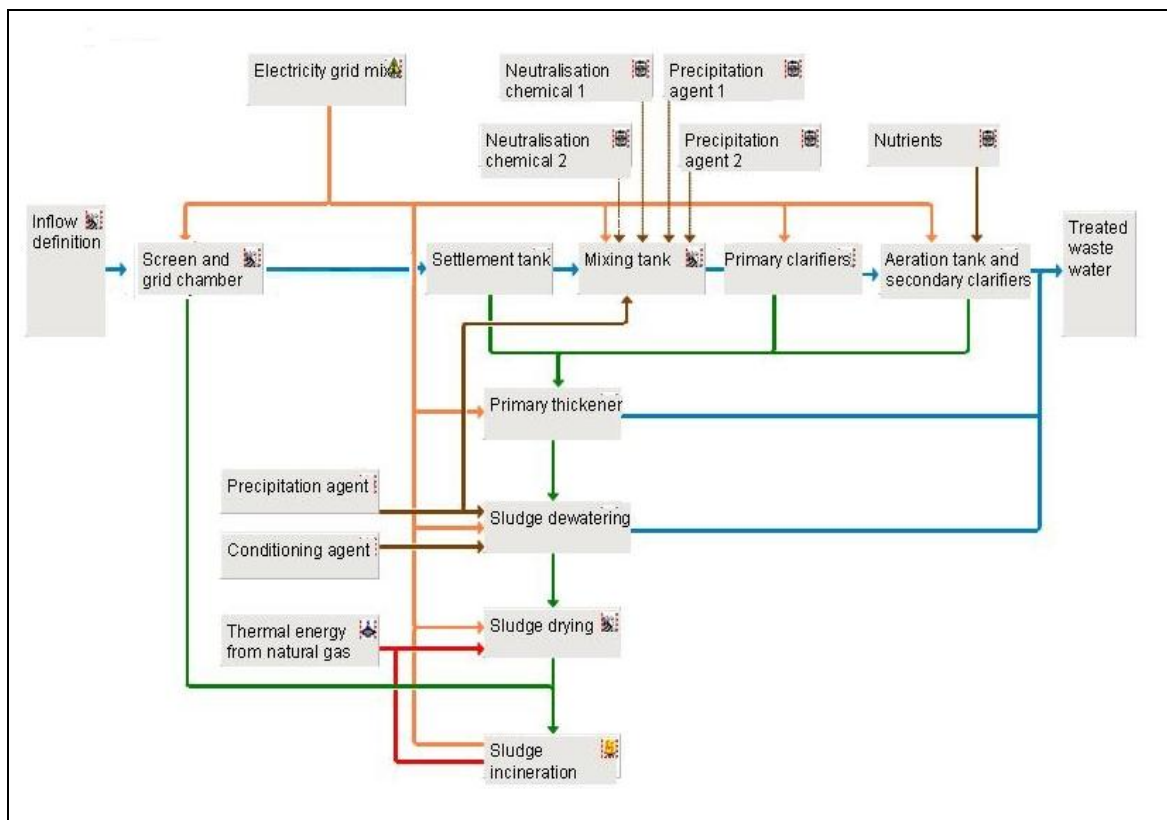


Figure 3.9. Modeling of wastewater treatment process in GaBi4.

Wastewater treatment data set consists of all relevant inputs and outputs from the treatment of incoming wastewater from industrial processes. It includes physical (screen and grid chamber), chemical (precipitation and neutralization) and biological treatment (activated sludge) steps and also treatment steps for the sludge disposal (thickening, dewatering, drying and incineration) as represented in Figure 3.9. Treated effluent directly gets in the natural surface water. According to unit process diagram of wastewater treatment plant, inventory analysis which involved parameters describing resources, material uses and emission to air, water and soil was quantified in the environmental impacts of one cubic meter wastewater treatment.

According to modeling principles; the influent water passes through the bar screens to remove all large objects (rags, remnants, etc.) carried in the stream. Next, wastewater is transported to the grit tank. So that, heavy particles can settle to the bottom to prevent damage to pumps or other equipments and to prevent their accumulation in sludge digestors. In the settlement tank content of suspended solids as well as the pollutant embedded in the suspended solids is reduced. Auxillaries of iron(II) sulfate ( $\text{FeSO}_4$ ), and calcium hydroxide ( $\text{Ca(OH)}_2$ ) are used as precipitant agents in the mixing tank. In addition to this, ( $\text{Ca(OH)}_2$ ) and sulphuric acid ( $\text{H}_2\text{SO}_4$ ) are used to regulate the pH value. Primary clarifier removes the suspended solids from the mixing tank prior to discharge to the aeration tank. The activated sludge converts organic substances into oxidized products, which is settled out in the secondary clarifiers. For this purpose, phosphoric acid ( $\text{H}_3\text{PO}_4$ ) is used as nutrient for micro-organisms to promote the growth of biological flocs that substantially removes organic material. The treated effluent in the secondary clarifier goes to natural surface water.

The settled solids, from the settlement tank, the primary clarifier and secondary clarifier are pumped to the primary thickener where the solids are thickened. Here, water content thickened sludge is accepted as 96 %. The thickened sludge is directly pumped to filter press for dewatering which use chemical flocculants to separate the water from the solids. After filter press, dewatered sludge with water content of 65% is obtained. Next, the sludge is dried with thermal energy. Water content of dried sludge is about 25%. The content from the screen and grit chamber is mixed with the dried sludge and is fed into the incinerator (Brauner, 2010).

In the modelled precipitation agents, nutrients, neutralisation chemicals and conditioning agents are consumed during treatment operations. So that, cradle to gate data sets have been chosen for  $\text{FeSO}_4$ ,  $\text{Ca}(\text{OH})_2$ ,  $\text{H}_2\text{SO}_4$  and  $\text{H}_3\text{PO}_4$ . Moreover, cradle to gate data sets are applied for thermal energy supply from natural gas and electricity generation (Brauner, 2010).

From water emissions point of view, COD was taken into account in order to analyze impact categories. In the light of LCA approach, input COD value and volume of influent water are adjusted taking 1299 mg/L for conventional bleaching dyeing recipe and 1821 mg/L for green dyeing recipe as baseline and were inserted into the GaBi4 software to calculate environmental impacts of wastewater treatment facilities for this thesis.

Sources of environmental impacts can be classified into four main groups; energy consumption, chemical consumption, sludge incineration and direct emissions due to breakdown of the organic matter (BOD/COD removal) in the wastewater. Sources of investigated and analyzed environmental impact categories due to their origin in wastewater treatment are given Appendices B (Tables B.3, B.6, B.9, B.12 and B.15).

### **3.2.10. T-Shirt Making up**

The process does not involve environmental concerns beyond the use of electricity for machines and fabric remnants produced during the cutting-to-size process. Hence, only energy consumption and input/output of fabric mass values have been taken into account to determine the main effective flows. Due to the negligible weight of needle oil, thread and water consumed for the steam pressing, they have been excluded from the study.

Several published data on cutting room waste level are available in the literature. For cotton products the total remnant of fabric can vary from 6 to 25% (Laursen et al., 1997). Another source states that stage related material losses are between 5-20 % (BTTG, 1999a). Apart from these values, another source states that the range in the cutting waste level is about 8% which is convenient to others. This represents an average value that covers all basic product types e. g., sweatshirts, T-shirt (U.S.EPA., 1996). The stage related

energy consumption is observed as 0.29 MJ/kg and 2 MJ/kg for the textiles (Laursen et al., 1997; BTTG, 1999b).

Reliable, scientific, updated data and through general observations carried out in the textile plant resulted that an average consumption of 2 MJ/kg textile can be assumed with a fabric loss of 10%.

### **3.2.11. T-shirt Use**

In this LCA study, this stage includes only wearing and washing of the T-shirt. Softening, drying and ironing are excluded from the study. Assessments of the environmental impacts from this stage are outlined by wash cycles, energy, water and detergent consumption. It has been assumed that each T-shirt can be washed with a lifetime of three years before being disposed of.

According to EC energy labeling criteria, “A” energy efficiency class washing machine has Specific Energy Consumption of  $\leq 0.19$  kWh/kg (standard programme cotton, 60°C) (95/12/EC, 1995). In European Union in 2005, approximately 10.3%, 64.8% and 5 % of washing machines sales were “+A”, “A” and “B” efficiency class respectively (EC, 2007). Regarding market share of machines, used data for electricity and water on washing machine are obtained from an average “A” energy efficiency class, front-loaded household machine with an average load of 6 kg (Bilgin, 2009). Detergent dosages differ strongly across the world due to regional hardness of water, contaminants on the laundry and capacity of washing machine. For Turkey, typical recommended detergent dose is assumed to be 225 g for per wash cycle (Yanık, 2008).

Consumption of energy, water and detergent over the lifetime of one T-shirt (50 washes before being disposed of) are calculated for assumptions on the subject: a 60°C wash without prewash, load mass of 6 kg, the detergent consumption of 225 g per load, typical water consumption of 49 liter per wash and electricity consumption of 1.14 kWh per wash and finally all calculations are adjusted for 1000 items of T-shirt.

### **3.2.12. Transport of Disposed T-shirt to Incineration Plant and Disposal**

During the disposal of used T-shirt, the transport stage includes collection and transport of waste T-shirt to the incineration plant. Similar transportation conditions are considered for all scenarios. Textiles can be disposed of in several ways. Incineration is selected as disposal way.

The full inventory of changes in resource consumptions and emissions to the environment is shown in Table A.1. All of the data in this table prepared in the light of inventory sources detailed above and used for interpretation of the life cycle impact assessment.

## 4. LIFE CYCLE IMPACT ASSESSMENT

LCA study starts with discovering and establishing a causal relationship between emissions resulting from inventory and an impact on the environment. The data summarized in the inventory phase are interpreted through classification, characterization, normalization and weighting stages using GaBi4 software.

As an initial step, prior to characterization, impact categories of acidification, aquatic eutrophication, terrestrial eutrophication, photochemical ozone formation (impact on vegetation) and global warming are selected, different inventory data of resources and emissions are quantified, then aggregated over the whole life cycle and classified into specific environmental impact categories, a so-called “cradle-to-grave” analysis.

Table 4.1 illustrates emissions, selected impacts categories related with these emissions and characterization units used in EDIP2003 methodology.

Table 4.1. Classification of emissions to impact categories and characterization units.

<b>Impact categories</b>	<b>Unit</b>	<b>Emissions</b>
Global warming	kg CO <sub>2</sub> - equivalent	CO <sub>2</sub> , CH <sub>4</sub> , N <sub>2</sub> O
Acidification	m <sup>2</sup> UES	NH <sub>3</sub> , SO <sub>2</sub> , NO <sub>x</sub>
Aquatic eutrophication	kg NO <sub>3</sub> -equivalent	NH <sub>3</sub> , NO <sub>x</sub> , NO <sub>3</sub> <sup>-</sup> , PO <sub>4</sub> <sup>-2</sup> , NH <sub>3</sub> /NH <sub>4</sub> <sup>+</sup>
Terrestrial eutrophication	m <sup>2</sup> UES	NH <sub>3</sub> , NO <sub>x</sub>
Photochemical ozone formation-impact on vegetation	m <sup>2</sup> UES *ppm*hours	NMVOC, CH <sub>4</sub> , NO <sub>x</sub>

Within each stage of the life cycle, consideration is given to the emissions profile. In addition to analyses conducted for LCIA, the emissions generated from entire life cycle of scenarios are evaluated and compared between Figure 4.1.a.- j.

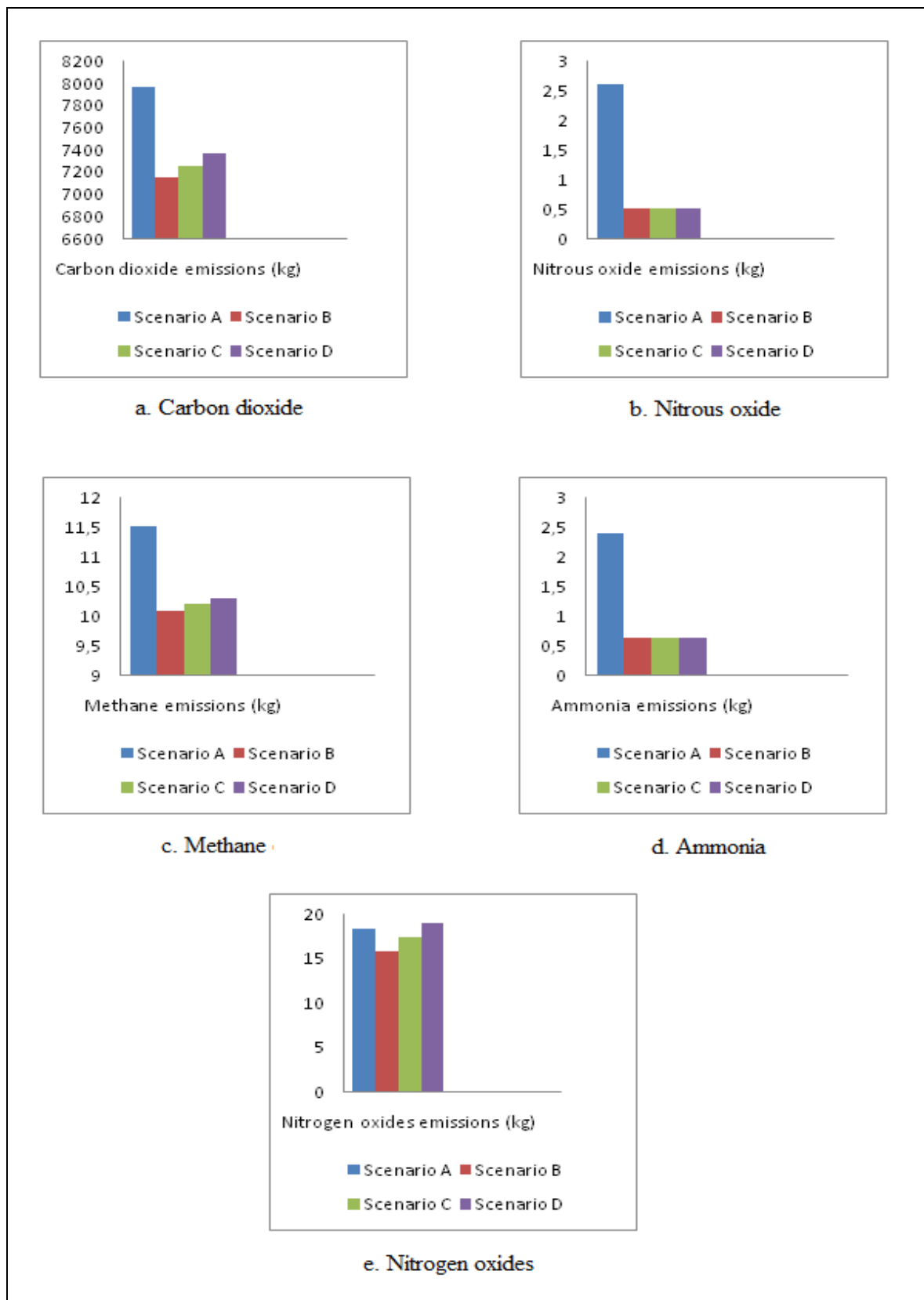


Figure 4.1. Quantities of emissions released from whole life cycle of scenarios (continued on the next page).

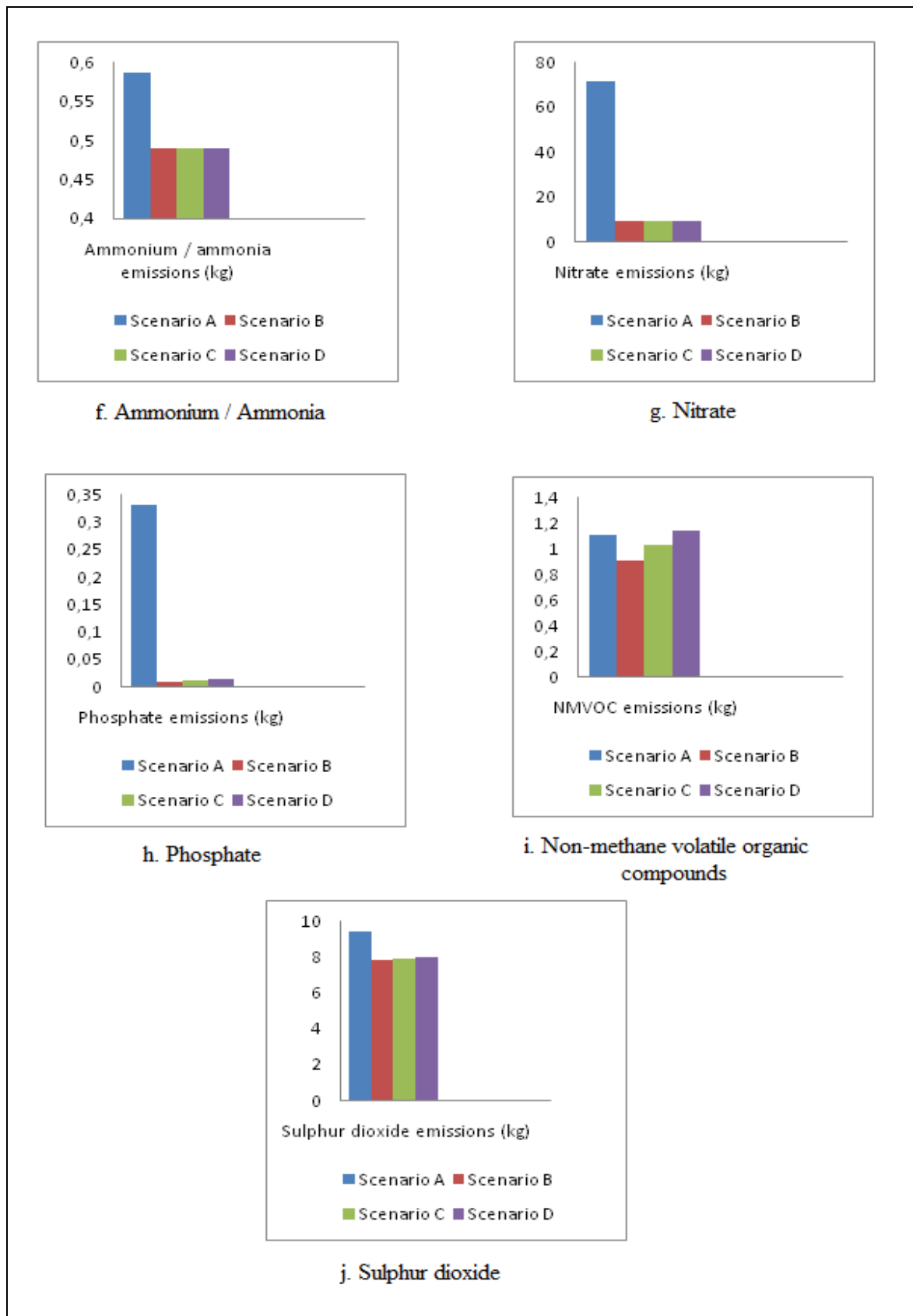


Figure 4.1. (Continued).

## 4.1. Characterization

The potential contributions from the emissions of the life cycle are calculated for all of the selected impact categories in the characterization. Characterization provides a way to directly compare the LCI results within each impact category.

When studying environmental impacts of products it is vital to avoid problem shifting from one geographical area to another. The site-generic and site-dependent characterization factors are part of the EDIP2003 methodology. Application of the site-dependent factors is restricted to the geographical region where an emission takes place. The site-generic factors can be based on the European average, or follow a worst-case approach by taking the highest characterization factors for the European area. Emissions from unknown region can be also calculated by using site-generic factors (Hauschild et al., 2003). In this LCA study, site-generic factors are applied to calculate environmental impact potentials of investigated life cycles. Figure 4.2 shows the equivalency factors which are shown under environmental quantities in GaBi4.

The figure displays two screenshots from the GaBi4 software interface, showing the characterization factors for two different environmental impact categories: Aquatic eutrophication and Global warming.

**Left Screenshot: EDIP 2003, Aquatic eutrophication [Environmental quantities] -- DB Quantity**

Name: EDIP 2003, Aquatic eutrophication  
Unit: Unit of NEP (EDIP)  
Associated side of balance: Outputs

Flow	1 kg NO3-Eq	Unit	1 [Flow] = * kg	Standar
Calcium nitrate [Ca(NO3)2] [Inorganic emissions to fresh water]	2,4213	kg	0,413	363 %
Nitrate [Inorganic emissions to air]	3,125	kg	0,32	0 %
Nitrate [Inorganic emissions to sea water]	1,4286	kg	0,7	0 %
Nitrate [Fresh water]	1,6949	kg	0,59	254 %
Nitrate [Inorganic emissions to fresh water]	1,6949	kg	0,59	254 %
Nitrate (as total N) [Inorganic emissions to sea water]	0,32248	kg	3,101	0 %
Nitrate (as total N) [Inorganic emissions to fresh water]	0,3826	kg	2,6137	57 %
Nitrite [Fresh water]	1,2555	kg	0,7965	188 %
Nitrite [Inorganic emissions to sea water]	1,0582	kg	0,945	0 %
Nitrite [Inorganic emissions to fresh water]	1,2555	kg	0,7965	188 %
Nitrogen (as total N) [Inorganic emissions to fresh water]	0,3826	kg	2,6137	57 %
Nitrogen (as total N) [Inorganic emissions to sea water]	0,32248	kg	3,101	0 %
Nitrogen dioxide [Inorganic emissions to air]	2,3148	kg	0,432	0 %
Nitrogen dioxide [Inorganic emissions to fresh water]	1,2555	kg	0,7965	188 %
Nitrogen dioxide [Inorganic emissions to sea water]	1,0582	kg	0,945	0 %
Nitrogen monoxide [Inorganic emissions to air]	1,5097	kg	0,6624	0 %
Nitrogen oxides [Inorganic emissions to sea water]	1,0582	kg	0,945	0 %
Nitrogen oxides [Inorganic emissions to fresh water]	1,2555	kg	0,7965	188 %
Nitrogen oxides [Inorganic emissions to air]	2,3148	kg	0,432	0 %
Phosphate [Fresh water]	0,10874	kg	9,196	16 %
Phosphate [Inorganic emissions to sea water]	0,13671	kg	7,315	0 %
Phosphate [Inorganic emissions to fresh water]	0,10874	kg	9,196	16 %
Phosphorus-pent-oxide [Inorganic emissions to sea water]	3,2468	kg	0,308	0 %

System: No changes. PE-GaBi 20 Last change: System, 01.03.2008

**Right Screenshot: EDIP 2003, Global warming [Environmental quantities] -- DB Quantity**

Name: EDIP 2003, Global warming  
Unit: Unit of GWP  
Associated side of balance: Outputs

Flow	1 kg CO2-Equiv	Unit	1 [Flow] =	Standar
1,1,1-Trichloroethane [Halogenated organic emissions]	0,0090909	kg	110	0 %
Ammonium carbonate [Inorganic emissions to air]	0,5	kg	2	0 %
Benzal chloride [Halogenated organic emissions to air]	1	kg	1	0 %
Carbon dioxide [Inorganic emissions to air]	1	kg	1	0 %
Carbon dioxide [Renewable resources]	1	kg	1	0 %
Carbon dioxide (biotic) [Inorganic emissions to air]	1	kg	1	0 %
Carbon dioxide, land transformation [Inorganic emissions to air]	1	kg	1	0 %
Carbon monoxide [Inorganic emissions to sea water]	0,5	kg	2	0 %
Carbon monoxide [Inorganic emissions to air]	0,5	kg	2	0 %
Carbon monoxide [Inorganic emissions to fresh water]	0,5	kg	2	0 %
Carbon monoxide (biotic) [Inorganic emissions to air]	0,5	kg	2	0 %
Carbon tetrachloride (tetrachloromethane) [Halogenated organic emissions]	0,00071429	kg	1400	0 %
Dichloromethane (methylene chloride) [Halogenated organic emissions]	0,011111	kg	9	0 %
Ethyl cellulose [Particulates to air]	0,5	kg	2	0 %
Halon (1301) [Halogenated organic emissions to air]	0,00017857	kg	5600	0 %
Hydrocarbons, chlorinated [Halogenated organic emissions]	1	kg	1	0 %
Methane [Organic emissions to air (group VOC)]	0,04	kg	25	0 %
Methane (biotic) [Organic emissions to air (group VOC)]	0,04	kg	25	0 %
Nitrous oxide (laughing gas) [Inorganic emissions to air]	0,003125	kg	320	0 %
NMVOG (unspecified) [Group NMVOG to air]	0,33333	kg	3	0 %
Perfluorobutane [Halogenated organic emissions to air]	0,00011628	kg	8600	0 %
Perfluorocyclobutane [Halogenated organic emissions]	0,0001	kg	10000	0 %
Perfluorohexane [Halogenated organic emissions to air]	0,00011111	kg	9000	0 %
Perfluoropentane [Halogenated organic emissions to air]	0,00011236	kg	8900	0 %

System: No changes. PE-GaBi 20 Last change: System, 01.03.2008

Figure 4.2. Equivalency factors in EDIP2003 methodology.

GaBi4 calculates the contribution of the emissions to each impact category and automatically classifies the emissions into relevant categories. Some of the emissions may affect multiple impact categories. The following calculation demonstrates how characterization factors are used to estimate environmental impact potential of global warming potential (GWP) and aquatic eutrophication potential (AEP) for scenario A:

The 100-year equivalency factors for GWP of CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O are 1, 25 and 320 respectively. These values represent the impact factor of each compound in relation to the GWP contribution of CO<sub>2</sub>. For an emission of 7963.7 kg CO<sub>2</sub>, 11.512 kg CH<sub>4</sub> and 2.6243 kg N<sub>2</sub>O, GWP for a time horizon of 100 years is determined by using Eq (2.1) as follows:

$$\begin{aligned}\Sigma EP_{(GWP)} &= \Sigma (7963.7 * 1 \text{ kg CO}_2 \text{ - eq}) \\ &+ (11.512 * 25 \text{ kg CO}_2 \text{ - eq}) \\ &+ (2.6243 * 320 \text{ kg CO}_2 \text{ - eq}) \\ &= 9091.3 \text{ kg CO}_2 \text{ - eq}\end{aligned}$$

Equivalency factors for AEP of NH<sub>3</sub>, NH<sub>3</sub>/NH<sub>4</sub><sup>+</sup>, NO<sub>x</sub>, NO<sub>3</sub><sup>-</sup> and PO<sub>4</sub><sup>-2</sup> are 0.8372, 2.1476, 0.432, 0.59 and 9.196 respectively. For an emission of 2.3912 kg NH<sub>3</sub>, 0.58604 kg NH<sub>3</sub>/NH<sub>4</sub><sup>+</sup>, 18.37 kg NO<sub>x</sub>, 71.745 kg NO<sub>3</sub><sup>-</sup> and 0.33725 kg PO<sub>4</sub><sup>-2</sup>, AEP is determined thus:

$$\begin{aligned}\Sigma EP_{(AEP)} &= \Sigma (2.3912 * 0.8372 \text{ kg NO}_3 \text{ - eq}) \\ &+ (0.58604 * 2.1476 \text{ kg NO}_3 \text{ - eq}) \\ &+ (18.37 * 0.432 \text{ kg NO}_3 \text{ - eq}) \\ &+ (71.745 * 0.59 \text{ kg NO}_3 \text{ - eq}) \\ &+ (0.33725 * 9.196 \text{ kg NO}_3 \text{ - eq}) \\ &= 56.627 \text{ kg NO}_3 \text{ - eq}\end{aligned}$$

Characterization results of selected impact categories and comparisons among all scenarios are presented in the Figures 4.3- 4.23. The figures represent the contribution of each compound for investigated life cycle stages.

#### 4.1.1. Characterization for Global Warming Potential

GWP states the cumulative radiative forcing value GHG over a defined time horizon, relative to the equivalent value for CO<sub>2</sub>. LCA approach uses equivalency factors with variable time horizons to account for the atmospheric residence time of each greenhouse gas emission, which can change the results very significantly. EDIP2003 methodology details the pollutants that contribute towards GWP for the 20, 100 and 500 year time horizon as specified by ISO and SETAC. The time horizon 100 year is chosen for this LCA study, as this is the standard time period used in the majority of LCA studies.

The substances considered as contributors to global warming are carbon dioxide (CO<sub>2</sub>), nitrous oxide (N<sub>2</sub>O) and methane (CH<sub>4</sub>) emissions. At an overall level, the scenarios indicate that cultivation and harvesting, yarn manufacturing, wet processing, and use stage are most effective stages contributing to GWP (Figures 4.3 - 4.6 and Table B.1).

Production of raw materials that include production of fertilizer and pesticide accounted for the significant portion (57%) of the total GWP, followed by N<sub>2</sub>O emissions from the application of N fertilizer to land (22%) and agricultural machinery operations (19%) in the conventional cotton cultivation stage. Among all chemical inputs, N fertilizer production accounts for a significant portion (50.8%) of the impact. A reduction in GWP is achieved by introducing CP strategies and replacing conventional methods with organic methods. GHG emissions decreased from 1194.8 to 219.9, 329.9 and 439.9 kg CO<sub>2</sub>-eq when organic cultivation methods used instead of conventional methods in scenario B, scenario C and scenario D with a productivity rate of 100%, 75% and %50 respectively (Figures 4.4-4.6 and Tables B.1-B.2.). The reason for increase in GWP is production and consumption of agricultural chemicals in conventional cotton cultivation.

Comparative analysis of the organic cotton cultivation stages given in Figures 4.4 – 4.6 and Table B.2, indicates that positive performance of organic cultivation with a productivity rate of 100% is due to smaller cultivation land area and correspondingly less amount of diesel consumption by the agricultural machinery operations in the field. Lower efficiency rates of cultivation depicted in 75% and 50% cultivation efficiency scenarios, require larger agricultural land areas which, in turn translate into higher diesel consumption and emissions values from the machinery causing higher GWP.

Kg CO<sub>2</sub>-eq decreased from 2420.7 to 1872.2 when conventional bleaching dyeing recipe is replaced with green dyeing recipe in the wet fabric processing, a 22% reduction in scenarios B, C and D (Figures 4.3-4.6 and Tables B.1-B.3). CO<sub>2</sub> emission reduction is the main factor leading to lower GWP when switching to green dyeing recipe. Comparing two dyeing recipes under investigation, 39.5% MJ/kg textile energy saving from using green dyeing recipe led to 177.9 kg CO<sub>2</sub>-eq reduction, 8% kg/kg textile chemical saving resulted in 40.75 kg CO<sub>2</sub>-eq reduction. Moreover, 40 percent decrease in wastewater volume is a cause of 330 kg CO<sub>2</sub>-eq reduction mostly caused by produced sludge volume. Energy generation and direct emissions resulting from breakdown of organic content have nearly equal importance in reduction.

The rank in the other effective stages for GWP from highest to lowest is yarn spinning, disposal, knitting, T-shirt making-up and ginning resulting from electrical energy requirement. Transportation is likely to make an insignificant contribution to GWP of the scenarios studied. In the system boundary, three transportation points are considered (Figure 3.1.) Among all transportation based global warming impact yarn transportation occupies the largest contribution (11.552 kg CO<sub>2</sub>-eq), followed by seed-cotton transportation (8.8917 kg CO<sub>2</sub>-eq) and finally transportation for disposal (0.63 kg CO<sub>2</sub>-eq). While mass of seed-cotton has the largest portion by weight, the transportation distance is shorter compared to other transportation based stages.

It can be clearly seen that the most important stage in the life cycle of T-shirt is use stage with a GWP of 4140.4 kg CO<sub>2</sub>-eq. In this stage, GWP is mainly caused by wastewater treatment and, in particular, generation of electricity for washing (32.6%). However, effect of detergent production constitutes 10.4% of the stage related total impact.

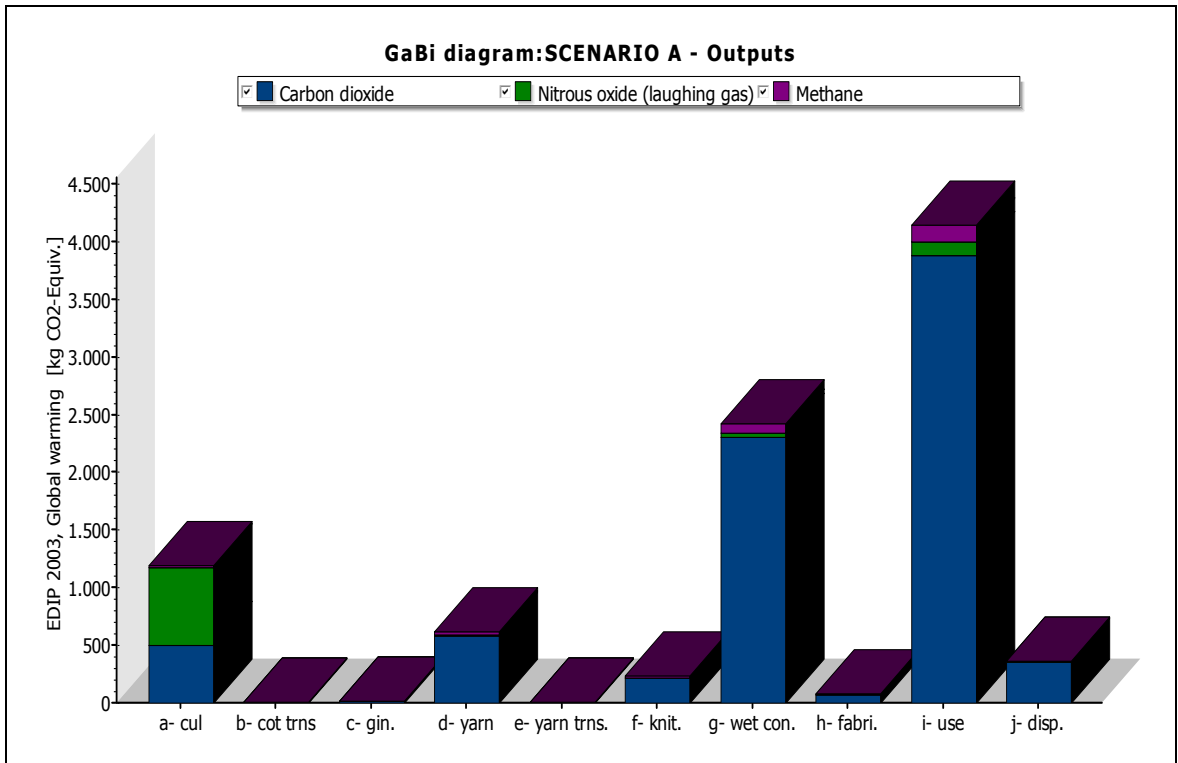


Figure 4.3. GWP for scenario A.

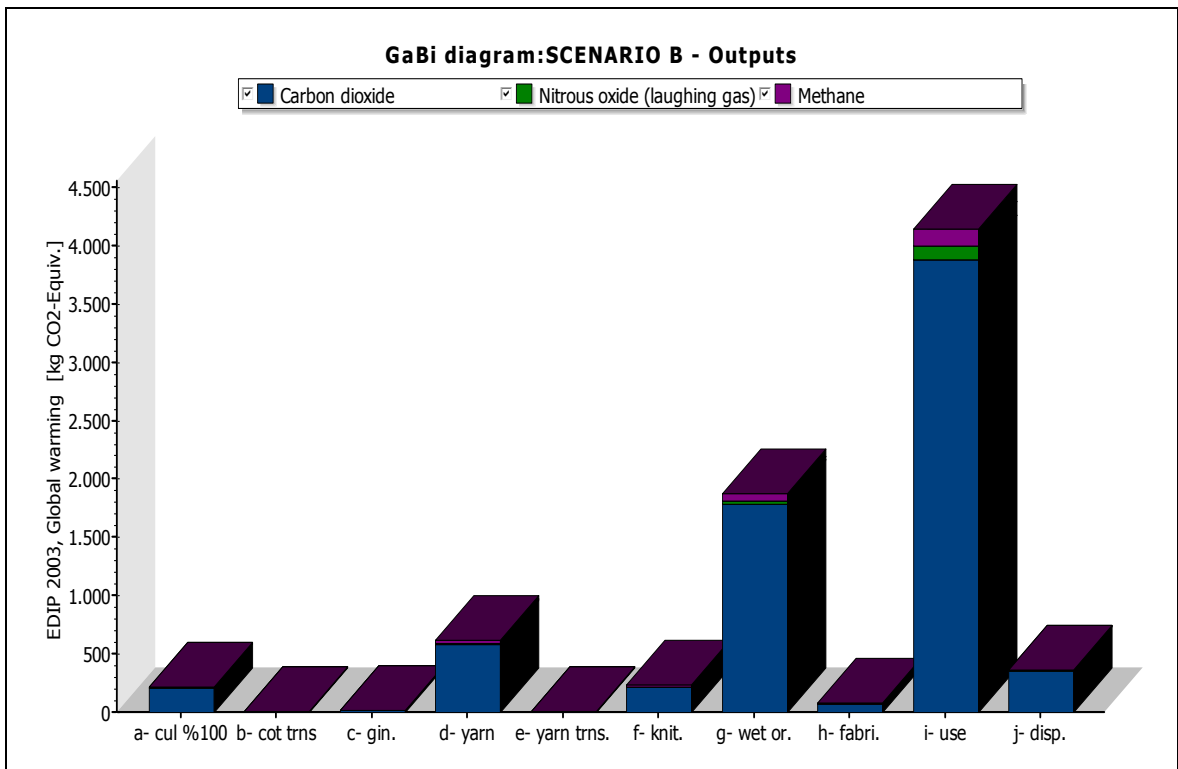


Figure 4.4. GWP for scenario B.

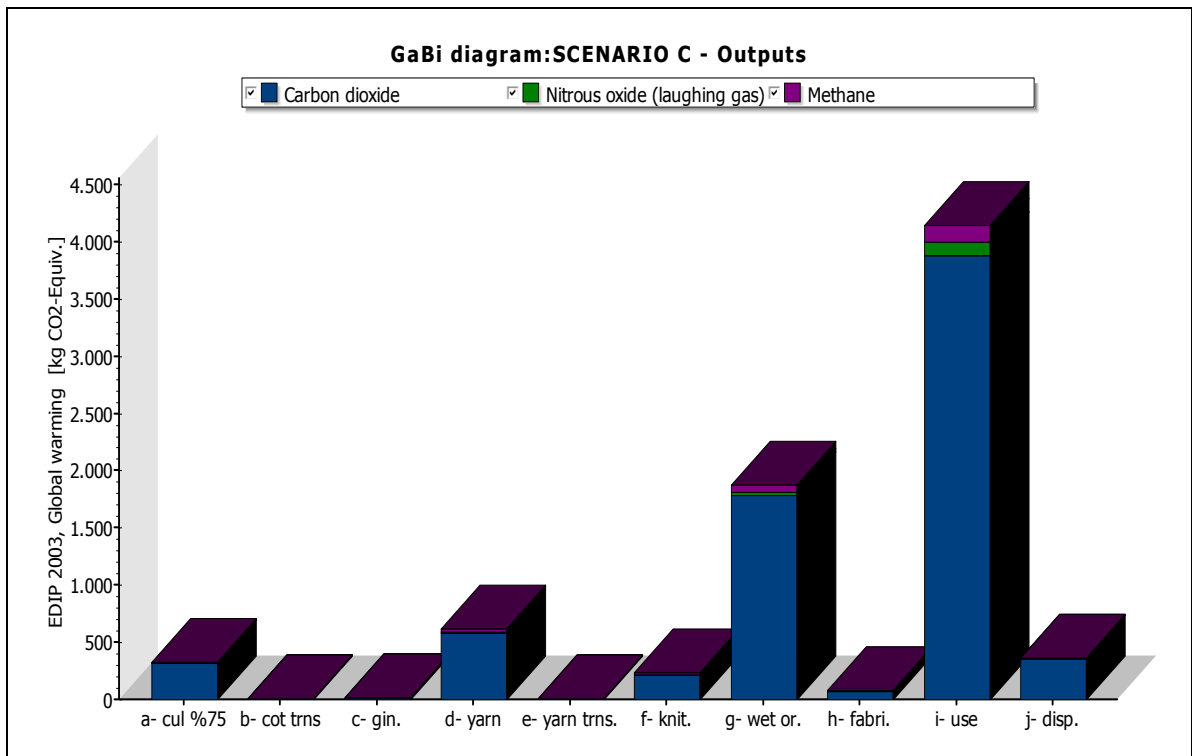


Figure 4.5. GWP for scenario C.

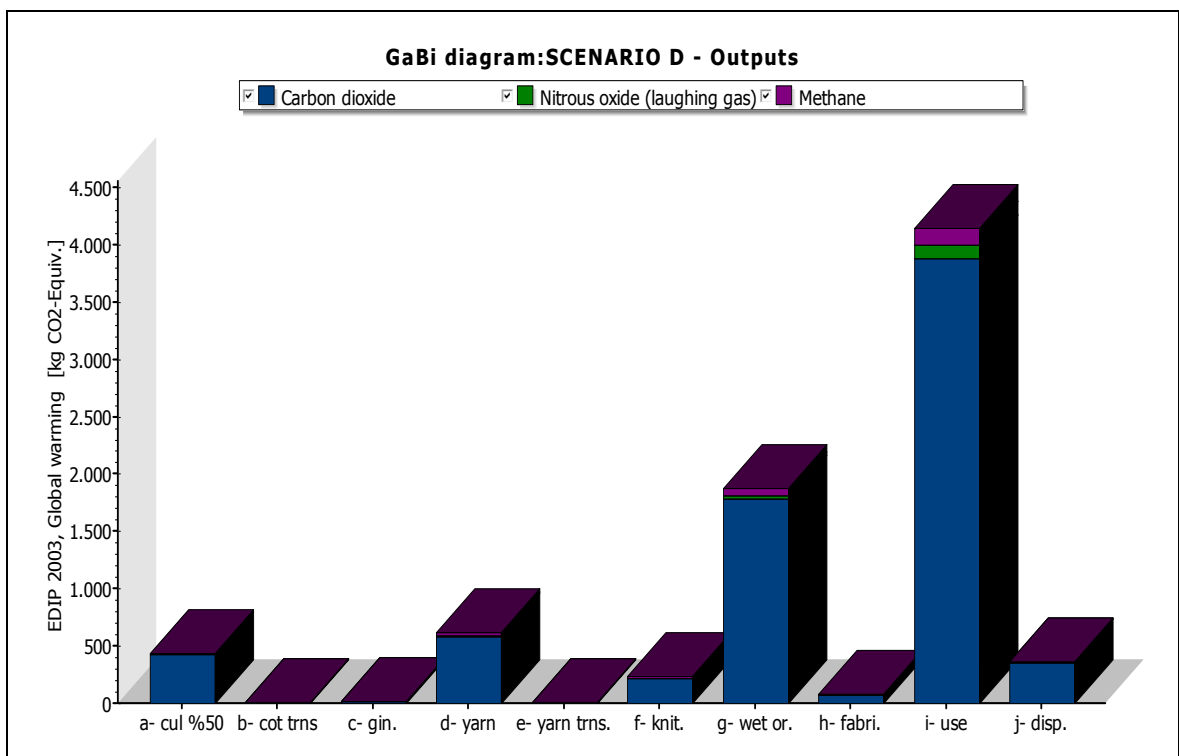


Figure 4.6. GWP for scenario D.

#### 4.1.2. Characterization for Acidification Potential

In EDIP2003 methodology, acidification potential (AP) is expressed as the full deposition area which is brought to exceed the critical load of acidification as a result of the emissions (area of unprotected ecosystem =  $\text{m}^2$  UES). Acidification is caused by the release of acidifying substances including sulfur dioxide ( $\text{SO}_2$ ), ammonia ( $\text{NH}_3$ ), and nitrogen oxides ( $\text{NO}_x$ ). Considering all investigated and compared scenarios, results indicate that cultivation and harvesting, yarn manufacturing, wet processing, and use stage are most effective stages causing AP (Figures 4.7 - 4.10 and Table B.4).

AP for conventional cotton cultivation stage is measured as  $104.3 \text{ m}^2$  UES in scenario A. Shifting from conventional cotton cultivation to organic cultivation reduces AP by  $74.5 \text{ m}^2$  UES for scenario B and  $59.6 \text{ m}^2$  UES for scenario C and  $44.7 \text{ m}^2$  UES for scenario D (Figures 4.7 - 4.10 and Table B.5). This corresponds to an acidifying gas emissions reduction of  $5.9 \text{ kg}$  for scenario B,  $4.312 \text{ kg}$  for scenario C and  $2.649 \text{ kg}$  for scenario D. Comparing cultivation scenarios  $\text{NH}_3$  is the main source of higher impact potential for conventional cultivation resulted from the supply and consumption of N fertilizer. Total  $\text{NH}_3$  emissions measured during the conventional cultivation stage is  $1.7723 \text{ kg}$  for per functional unit. N fertilizer consumption represented  $75.56 \%$  of this value resulting from volatilization during and after application of urea, whereas N fertilizer production only accounted for  $23.1\%$  of total ammonia emissions emitted. Secondly, a decline in  $\text{SO}_2$  is observed. Diesel combustion by farm machinery for spraying operations is the principal source of difference during conventional cultivation stage. Moreover, fluctuations for AP among organic cultivation scenarios only depends on land area correspondingly combustion and production of diesel for farm machinery.

In comparison to conventional bleaching dyeing recipe with green dyeing recipe in the wet fabric processing stages, a reduction in AP by  $17 \text{ m}^2$  UES is observed when green dyeing recipe is implemented for scenarios of B, C and D (Figures 4.7 - 4.10 and Table B.6). Wastewater treatment is a crucial factor to determine stage related AP which accounted for nearly  $70$  percent of total impact for both dyeing implementation where sulphur dioxide and nitrogen oxide equivalents share half of total impact. Steam used for heating, and electricity used for mechanical work use plays an important role in measured

AP for considered stages. However, magnitudes of environmental improvements obtained by replacing the conventional bleaching dyeing process with green dyeing process are highly dependent on chemical saving rather than energy saving. In detail, energy saving from using green dyeing recipe resulted in 2.64 m<sup>2</sup> UES reduction, chemical saving led to 2.83 m<sup>2</sup> UES reduction. Considering water conservation which equals to 60 L/kg textile is unimportant focus point from the point of LCA perspective with a reduction of 0.015 m<sup>2</sup> UES. Moreover, as presented in Table B.6 energy consumption, sludge incineration and direct emissions originated from COD removal share total impact equally from the point of wastewater treatment facilities. However, chemical consumption is negligible.

AP for ginning (1.427 m<sup>2</sup> UES), yarn manufacturing (16.40 m<sup>2</sup> UES), knitting (6.190 m<sup>2</sup> UES) and T-shirt making-up (2.094 m<sup>2</sup> UES) stages are revealed in connection with electricity generation for processing. The impact potential from ginning and T-shirt making up are insignificant and unlikely to affect the overall results of AP for all scenarios. Moreover, incineration where energy is recovered in the form of power and heat is notable with an AP of 5.4553 m<sup>2</sup> UES (Figures 4.7 - 4.10 and Table B.4).

Use stage is an effective contributor to acidification with potential of 159.5 m<sup>2</sup> UES. In this stage, wastewater treatment is predominantly contribute to the impact (51%) and, in particular, soap production (25.3%) and generation of electricity consumed for washing (22.4%). However, contribution from consumption of tap water is negligible for washing (Figures 4.7 - 4.10).

Transports among system boundaries do not have any significant effect on AP for all scenarios under investigation. The primary contribution originates from transport of yarn (0.860 m<sup>2</sup> UES). It is followed by transport of seed-cotton (0.668 m<sup>2</sup> UES) and finally transport of used T-shirts for disposal (0.0471 m<sup>2</sup> UES). The main part of this stages' contribution originates from unburnt fuels in connection with transport rather than production of energy source.

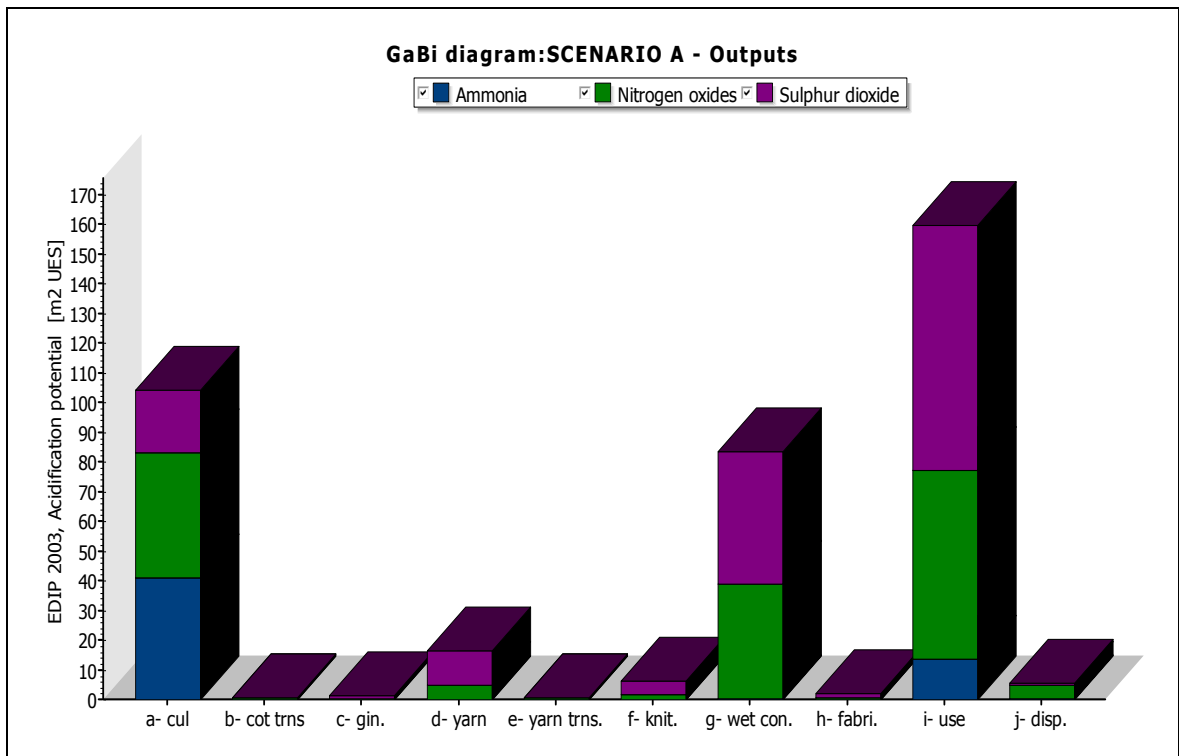


Figure 4.7. AP for scenario A.

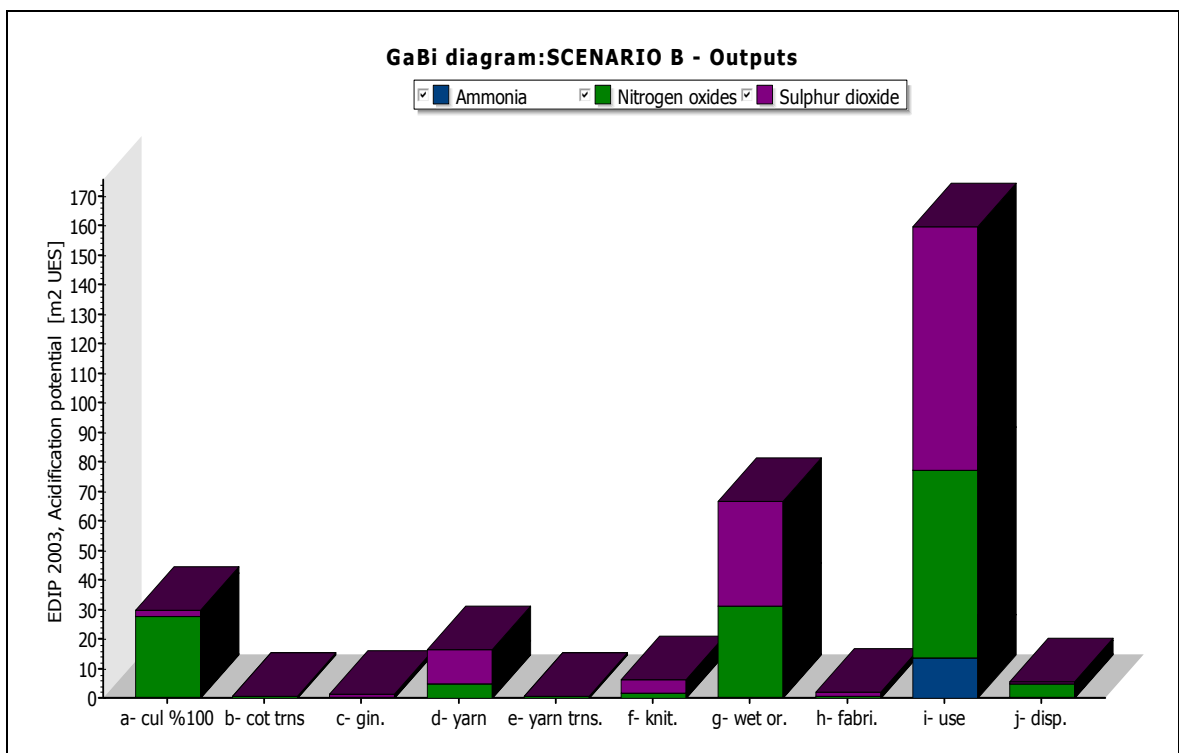


Figure 4.8. AP for scenario B.

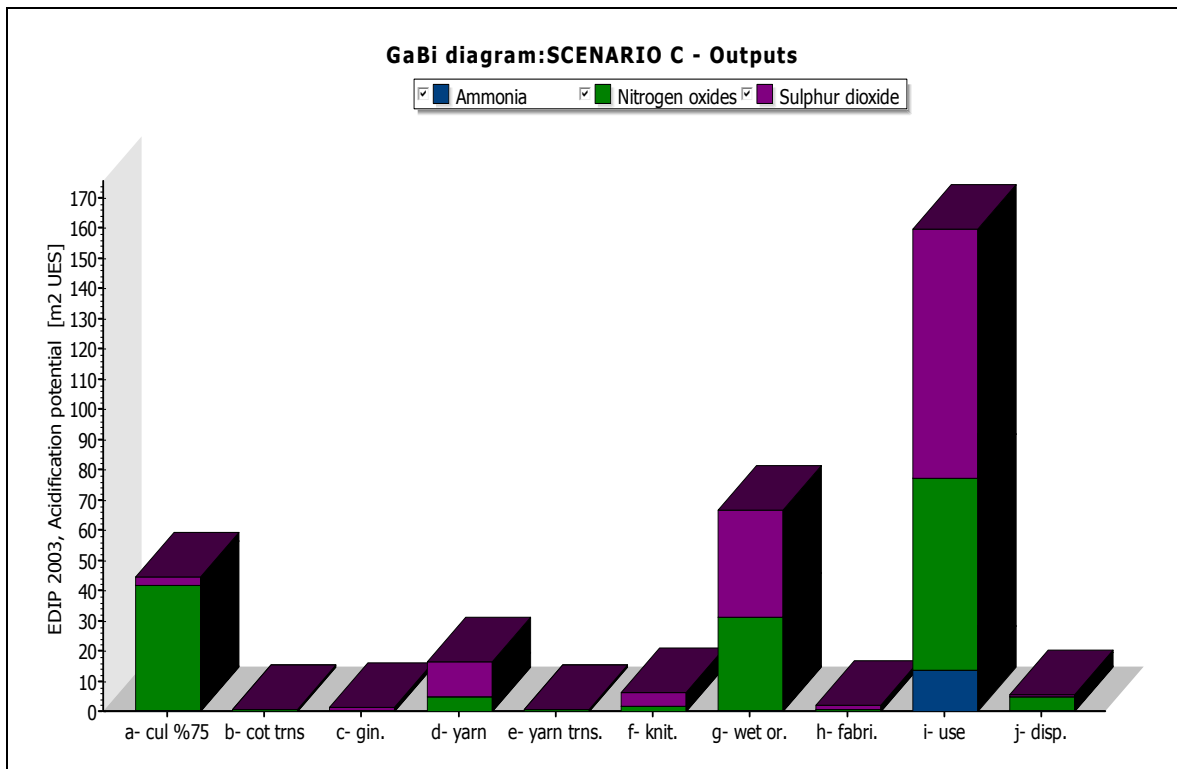


Figure 4.9. AP for scenario C.

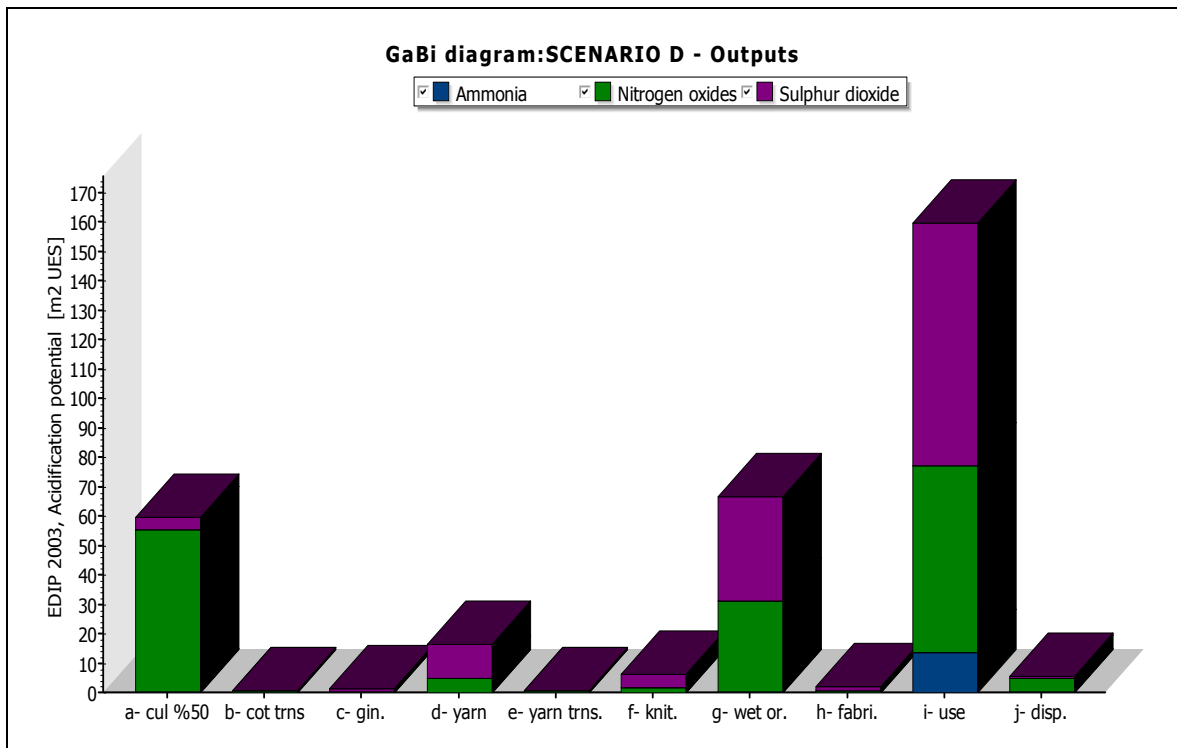


Figure 4.10. AP for scenario D.

#### 4.1.3. Characterization for Aquatic Eutrophication Potential

Important source of N and P emissions to surface waters are deposition of airborne  $\text{NO}_x$  and  $\text{NH}_3$  on surface waters from combustion processes and livestock farming, direct effluents of N and P and diffuse losses of N via leaching (Klepper et al., 1995).

Hauschild et al. (2003) applied the CARMEN (Cause effect Relation Model to support Environmental Negotiations) model, in EDIP2003 to analyze and evaluate strategies to reduce nutrient loading of inland waters and coastal seas in Europe. CARMEN model uses three main sources for nitrogen and phosphorus to surface water which are agriculture, municipal wastewater and atmospheric deposition (only for nitrogen). The total discharge of nutrient is calculated by combining land based (agricultural and atmospheric) and population based (wastewater) inputs per region. It is a detailed modelling of the transport of nutrients from agricultural supply and atmospheric deposition through groundwater drainage and surface runoff or topsoil erosion to surface water. Model does not explicitly address eutrophication of lakes, but lakes will usually be part of a river catchment.

In life cycle impact assessment, it should be considered that not all of the nutrients initially released to air and soil actually turn out in surface waters and make a contribution to eutrophication. In order to calculate the approximation of N deposition on surface waters, fate factors are developed which are used in the calculation of AEP of ammonia ( $\text{NH}_3$ ) and nitrogen oxide ( $\text{NO}_x$ ) air emissions for Europe and a number of European regions (Huijbregts et al., 2000). The factors indicate which fraction of a  $\text{NO}_x$  or  $\text{NH}_3$  emission released in different European countries reaches to the marine ecosystems. The calculation is based on the original RAINS (Regional Air Pollution Information and Simulation) model, which has been developed as a tool for evaluation of acidification and terrestrial eutrophication potential in Europe (Huijbregts, 2002).

The overall life cycle for selected product, the eutrophying impact is typically characterized by the release of ammonia ( $\text{NH}_3$ ), nitrogen oxides ( $\text{NO}_x$ ), nitrate ( $\text{NO}_3^-$ ), phosphate ( $\text{PO}_4^{-2}$ ) and ammonia/ammonium ( $\text{NH}_3/\text{NH}_4^+$ ) as summarized in Figures 4.12 - 4.15.

Air and water emissions causing AEP is illustrated in Figure 4.11. Taking into account scenarios B, C and D aquatic nutrient enrichment is predominantly caused by  $\text{NO}_x$  emissions deposited to marine areas, while the contribution from the waterborne emissions has smaller contribution rate. Contrary to others, scenario A representing life cycle of conventional T-shirt is mostly affected by waterborne emissions.

Conventional cultivation covers all determined sources of AEP, the most important of which are nitrate and phosphate. The equivalent of 43.561 kg of  $\text{NO}_3^-$  is produced during the production of conventional cotton.  $\text{NO}_3^-$  contributed 36.736  $\text{NO}_3^-$  eq (84.3% of total),  $\text{NH}_3$  contributed 1.4837 kg  $\text{NO}_3^-$ -eq (3.4%),  $\text{NO}_x$  contributed 2.1293 kg  $\text{NO}_3^-$ -eq (4.9%),  $\text{PO}_4^{2-}$  contributed 3.0542 kg  $\text{NO}_3^-$ -eq (7%) and  $\text{NH}_3/\text{NH}_4^+$  contributed 0.10769 kg  $\text{NO}_3^-$ -eq (0.4%) (Figure 4.12). A reduction in the impact potential is achieved by shifting conventional method to organic cultivation methods. Nutri-fying emissions decreased from 43.561 to 1.4603, 2.1904 and 2.9205 kg  $\text{NO}_3^-$ -eq when organic cultivation methods used instead of conventional methods in scenario B, C and D respectively (Figures 4.12 - 4.15 and Table B.8). This is because fertilizer used in conventional cotton cultivation cause excessively notable portion in contrast to organic cotton cultivation, where natural alternatives to agrochemicals are used. When taking into all contributor stages, fertilizer consumption consists of 92% of stage related total impact. Moreover, AEP arisen from organic cultivation caused by nitrogen oxides mostly are due to energy generation for agricultural operations. Irrigation and cotton-seed production are insignificant contributors for this stage (Table B.8).

8.9529 kg  $\text{NO}_3^-$ -eq has been revealed in use stage (Figures 4.12 - 4.15). Nitrogen oxides and nitrate are significant contributors of the impact in use stage. In this stage, the impact is mainly forced by wastewater treatment (4.163 kg  $\text{NO}_3^-$ -eq) and detergent production (4.1938 kg  $\text{NO}_3^-$ -eq). However, effect of power generation constitutes 6% of the stage related total impact.

When conventional bleaching dyeing recipe is compared with green dyeing recipe in the wet fabric processing stages, a reduction in AEP by 0.7207 kg  $\text{NO}_3^-$ -eq (21.3%) is observed (Figures 4.12-4.15 and Table B.9). Wastewater treatment is a vital contributor to stage related AEP accounting for nearly 80% of total impact for both dyeing recipe. Direct

emissions released from breakdown of the organic content of the waster contribute to about 56-59% of the total impact of wastewater treatment. Similarly, effect of sludge incineration to aquatic eutrophication 40 percent of stage related total impact. However, sum of chemical and electricity consumption are insignificant part of the potential source when whole treatment stage is taken into account (Table B.9). From the point of wet processing applications placed in dyehouse, chemical consumption is observed as one of the main focus point with a contribution rate of 12% and 14% for conventional dyeing recipe and green dyeing recipe respectively. Sum of steam and electricity are insignificant part of the potential source (3-4%). Switching dyeing preference from conventional to green resulted in 0.7207 kg NO<sub>3</sub><sup>-</sup>-eq reduction. The reduction is mainly due to steam consumption (41%), power generation (26%), wastewater treatment (22%) and saving in chemical consumption (10%) (Table B.9).

Aquatic eutrophication potential of transport of seed-cotton (0.0295 kg NO<sub>3</sub><sup>-</sup> eq), ginning (0.025 kg NO<sub>3</sub><sup>-</sup>-eq), yarn manufacturing (0.2626 kg NO<sub>3</sub><sup>-</sup>-eq), transport of yarn (0.038 kg NO<sub>3</sub><sup>-</sup>-eq), knitting (0.0991 kg NO<sub>3</sub><sup>-</sup>-eq), T-shirt making-up (0.0335 kg NO<sub>3</sub><sup>-</sup>-eq) and disposal (0.2432 kg NO<sub>3</sub><sup>-</sup>-eq) are insignificant considering cultivation, wet processing and use stage (Figures 4.12 - 4.15 and Table B.7).

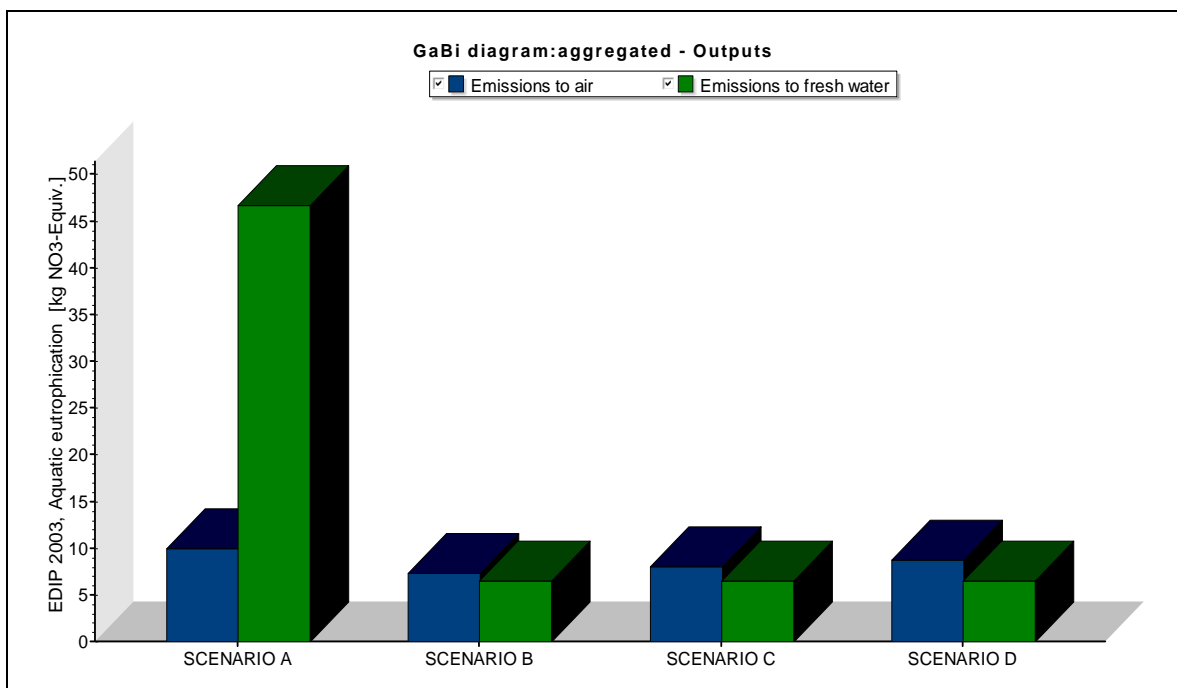


Figure 4.11. Air and fresh water emissions causing aquatic eutrophication.

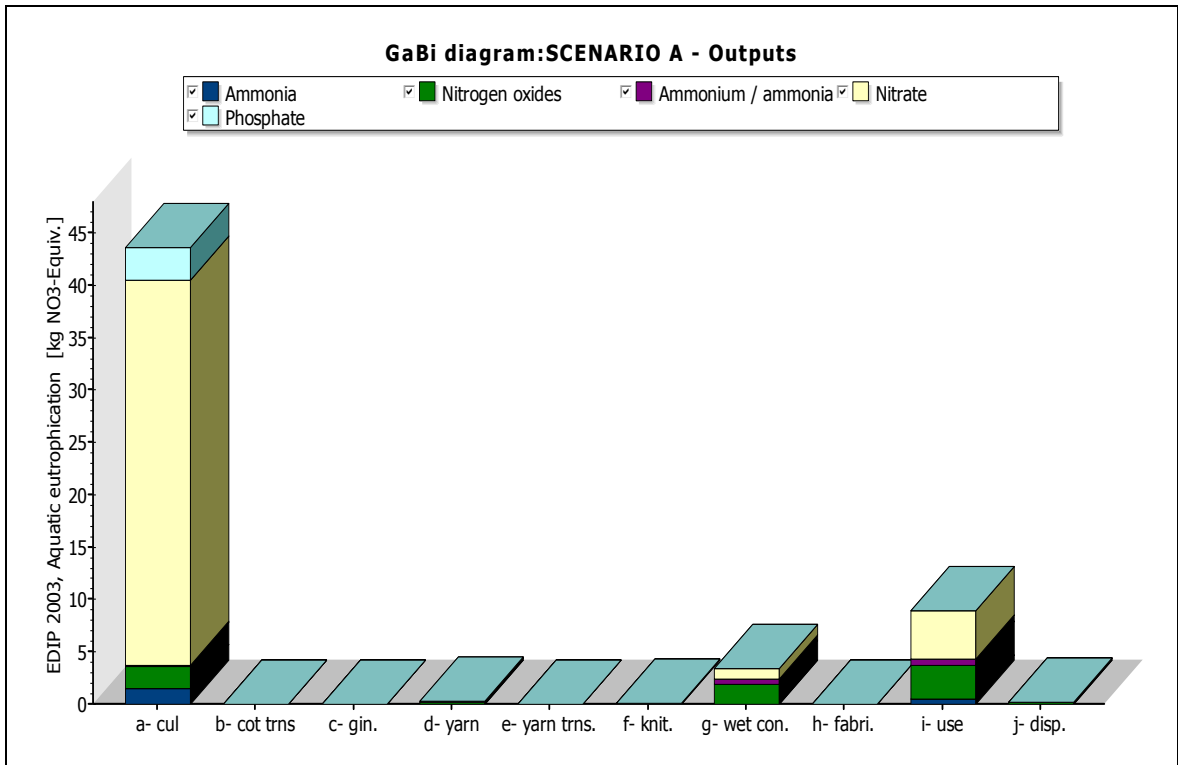


Figure 4.12. AEP for scenario A.

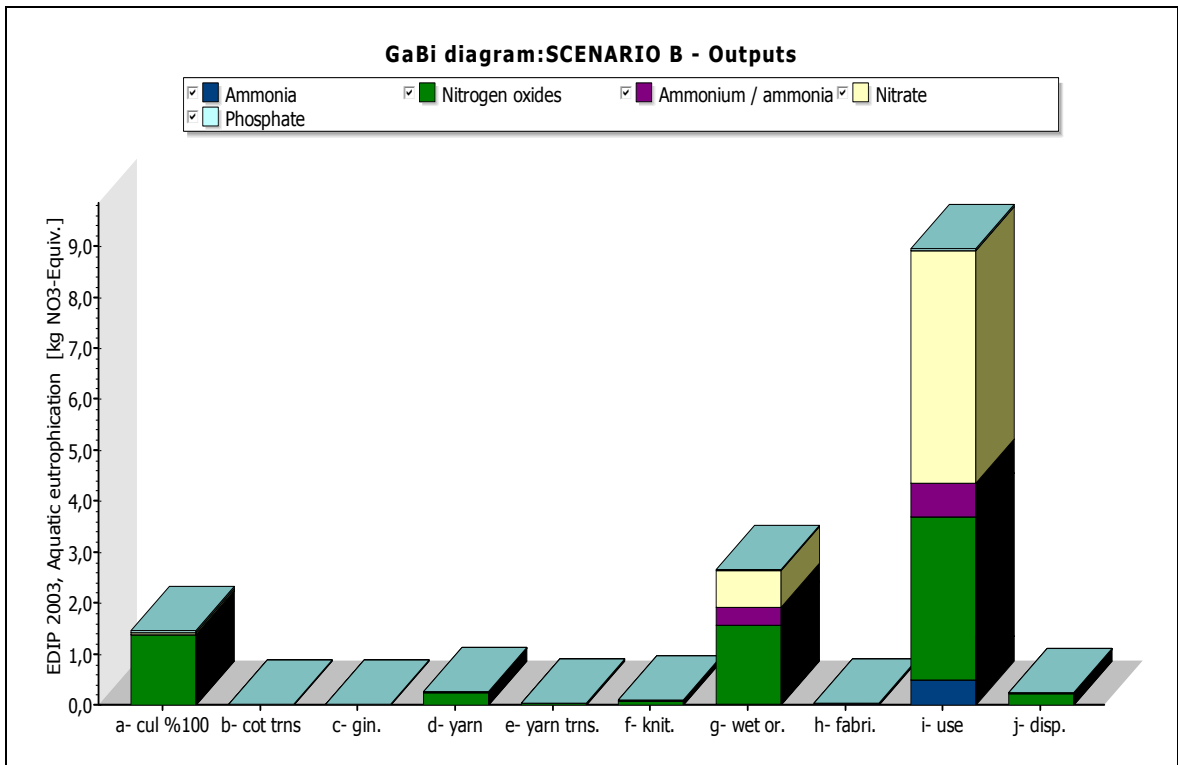


Figure 4.13. AEP for scenario B.

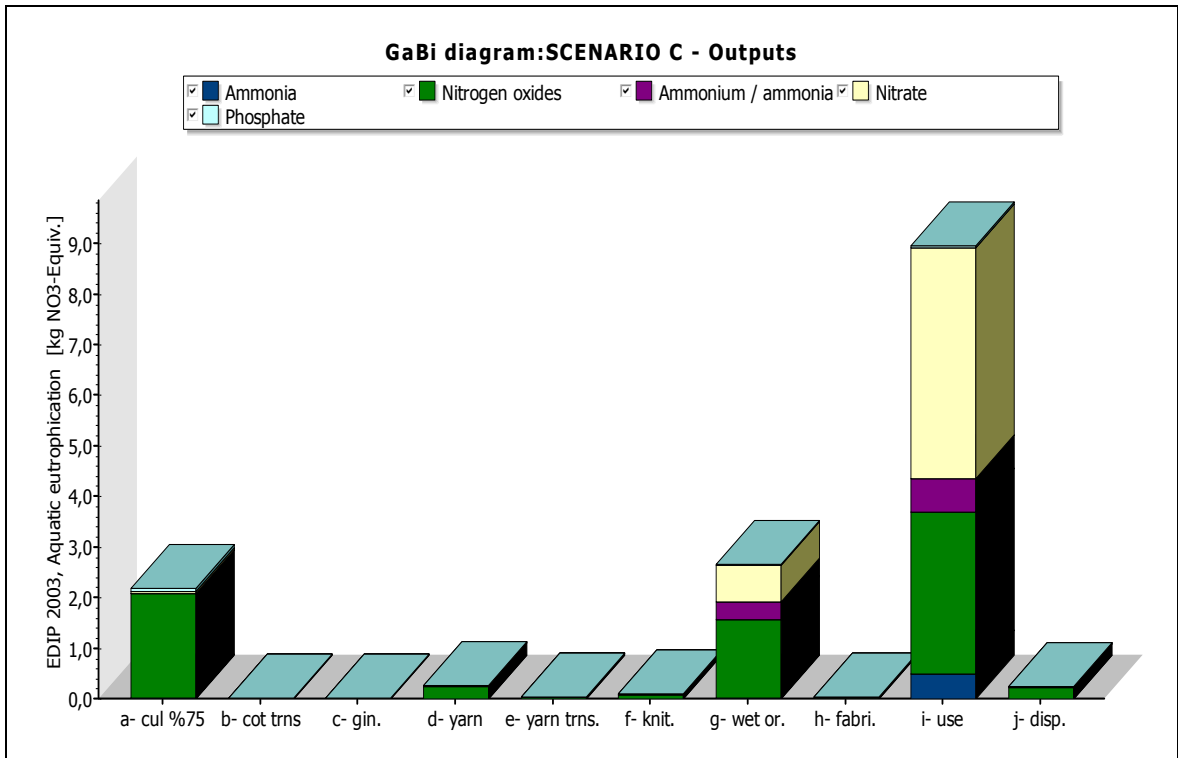


Figure 4.14. AEP for scenario C.

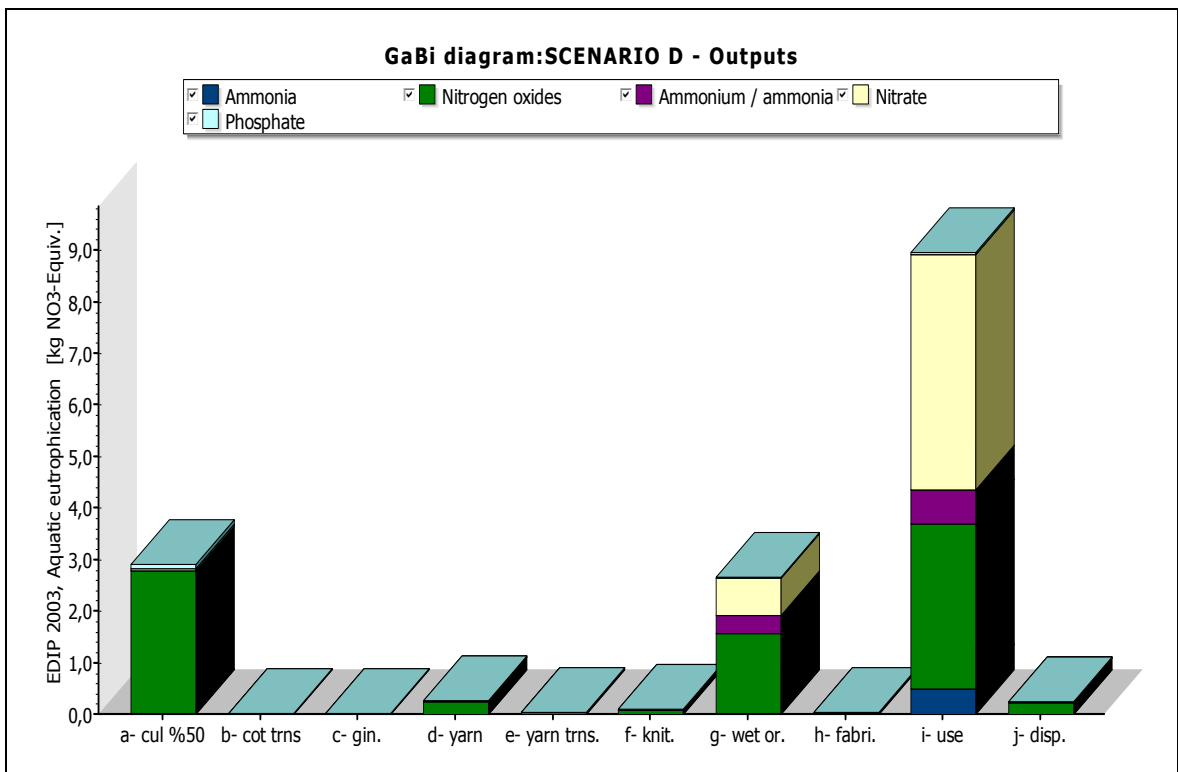


Figure 4.15. AEP for scenario D.

#### 4.1.4. Characterization for Terrestrial Eutrophication Potential

Since nitrogen is the most important limiting factor for terrestrial ecosystems, characterization for terrestrial eutrophication potential (TEP) considers mainly eutrophication effects of  $\text{NO}_x$  and  $\text{NH}_3$  emissions. In EDIP2003 methodology, TEP is expressed in  $\text{m}^2$  UES. In this comparative LCA study effects of  $\text{NO}_x$  and  $\text{NH}_3$  emissions are considered (Figures 4.16- 4.19 and Table B.10).

TEP for conventional cotton cultivation stage is measured as  $304.2 \text{ m}^2$  UES in scenario A (Figure 4.16). Results of comparative analysis indicated that the impact potential falls by 73, 60 and 46 percent for the changed choice of raw materials, reduction in the use of fuels and reorganization of the structure of agricultural productivity in cultivation stage for scenario B, C and D respectively (Table B.11). Net results for TEP of organic cultivation stage are shown in Figures 4.17-4.19 and Table B.11 which shows that environmental benefit of the cultivation is increased, if the productivity of agricultural yields is increased in course of time.

From wet processing points of view, 20 % of decrease is observed when conventional bleaching dyeing recipe is replaced with green dyeing recipe. When considering wet processing in dyehouse the main reason is that smaller amount chemicals used in the process save considerable amounts of energy and water, because process temperature is decreased and several baths are avoided (Table B.12). Moreover, taking into account the wastewater treatment facilities sludge incineration and direct emissions from COD/BOD removal represent 40% of the stage related impact. Energy and chemical consumption are insignificant focus points (Table B.12).

TEP of transport of use stage is observed as  $247.1 \text{ m}^2$  UES. Moreover, seed-cotton transportation ( $1.74 \text{ m}^2$  UES), ginning ( $1.451 \text{ m}^2$  UES), yarn manufacturing ( $14.36 \text{ m}^2$  UES), transport of yarn ( $2.234 \text{ m}^2$  UES), knitting ( $5.422 \text{ m}^2$  UES), T-shirt making-up ( $1.835 \text{ m}^2$  UES) and disposal ( $14.26 \text{ m}^2$  UES) are other impact potential results which are unlikely to affect the overall results (Figures 4.16 - 4.19 and Table B.10).

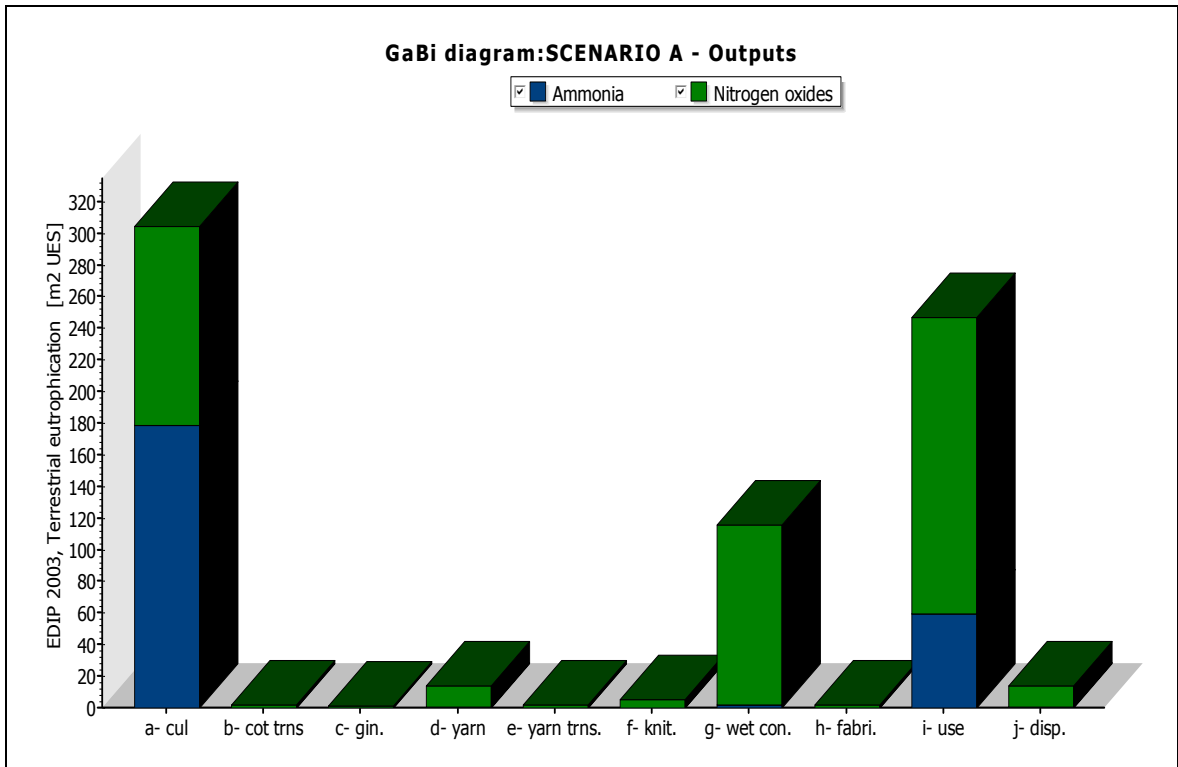


Figure 4.16. TEP for scenario A.

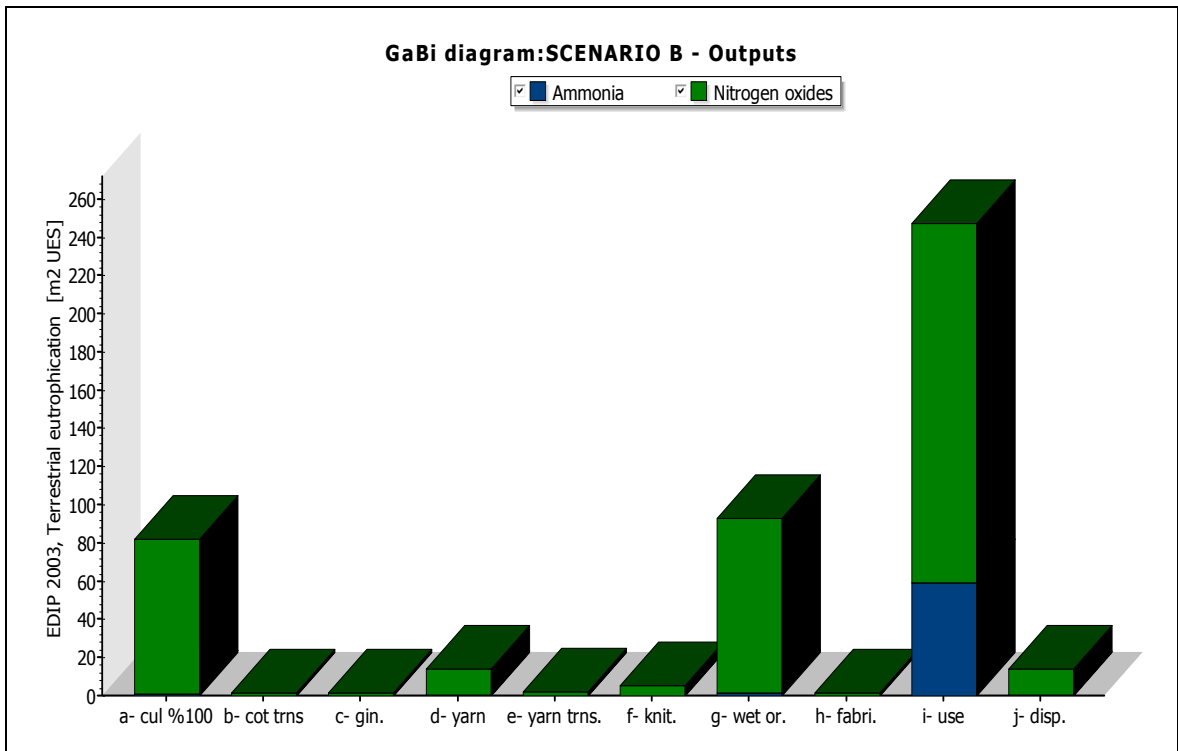


Figure 4.17. TEP for scenario B.

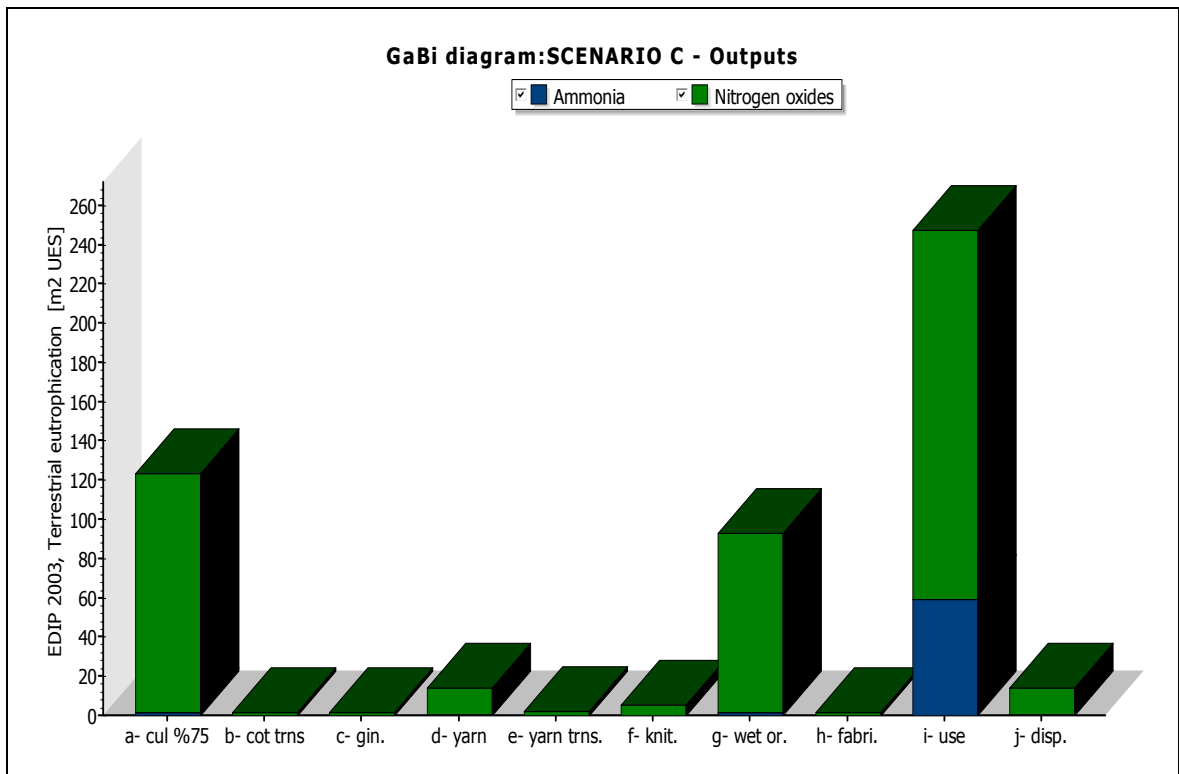


Figure 4.18. TEP for scenario C.

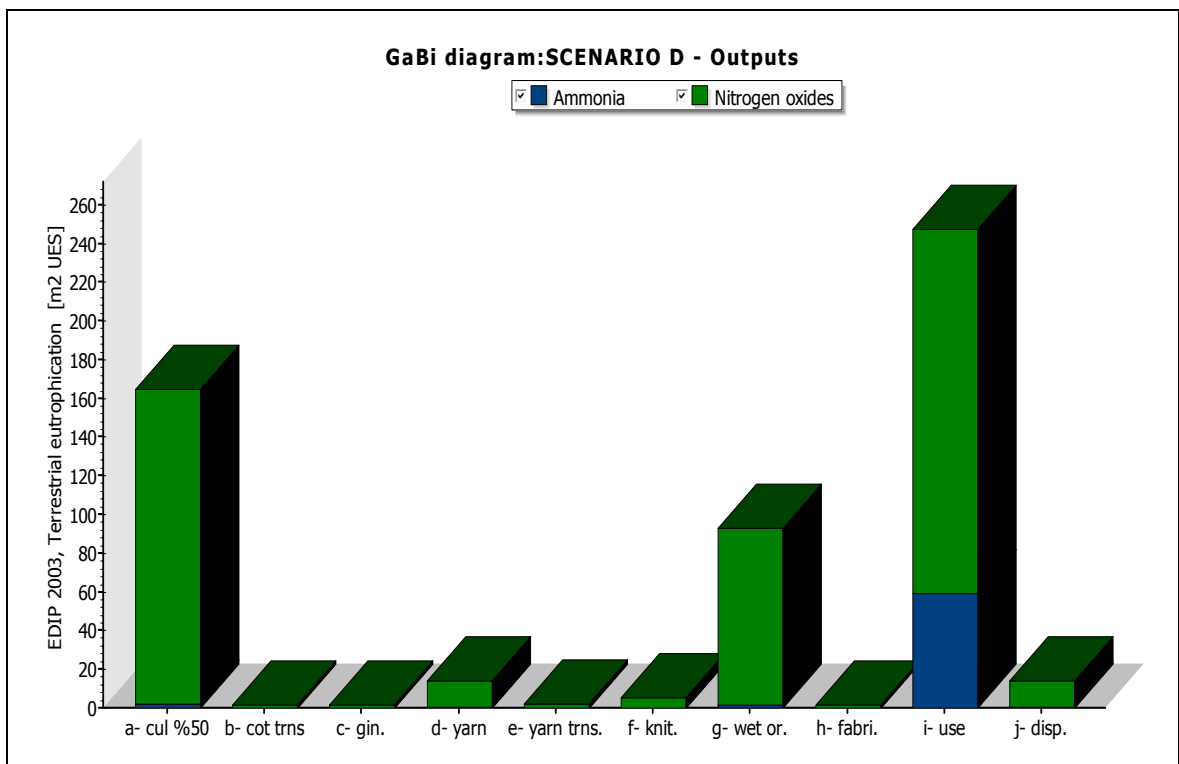


Figure 4.19. TEP for scenario D.

#### 4.1.5. Characterization for Photochemical Ozone Formation Potential - Impact on Vegetation

Nitrogen oxides (NO<sub>x</sub>), non-methane volatile organic compounds (NMVOC), and methane (CH<sub>4</sub>) are substances contributing to this impact category. Photochemical ozone formation potential - impact on vegetation (POFP - impact on vegetation) is expressed in m<sup>2</sup> UES\*ppm\*hours. Figures 4.20-4.23 and Table B.13 indicate that considering whole scenarios cultivation and harvesting, wet processing and use stage are effective contributors to POFP - impact on vegetation.

Environmental impact potential for conventional cotton cultivation stage is calculated as 9509.7 m<sup>2</sup> UES\*ppm\*hours in scenario A. In conventional cotton cultivation most of impact potentials come from N fertilizer production and diesel combustion. Organic cultivation production leads to a decline the potential by 36.5% and 4.6% for scenarios B and C. Contrary to others, only in scenario D an increase of 27% is observed resulting from agricultural land area correspondingly combustion and production of diesel for farm machinery (Figures 4.20-4.23 and Table B.14).

When conventional bleaching dyeing recipe is compared with green dyeing recipe, a decline in impact potential by 1926.4 m<sup>2</sup> UES\*ppm\*hours (20.1%) is observed (Table B.15). Wastewater treatment facility is a vital contributor to stage related potential accounting for nearly 72 percent of total impact for both implemented dyeing recipe. Moreover, sum of steam and electricity (8.43%) are insignificant part of the potential source when taking into account productions of chemicals (18.8%). Switching dyeing preference from conventional to green recipe resulted in 1926.4 m<sup>2</sup> UES\*ppm\*hours reduction. This saving is mainly due to reduction in wastewater treatment (68%), steam consumption (16%), saving in chemical consumption (13.3%) and finally power generation (3.6%). Moreover, water 60 L/kg water saving between two recipe is insignificant part of potential.

The characterized environmental impact potential of transport of seed-cotton (129.49 m<sup>2</sup> UES\*ppm\*hours), ginning (132.79 m<sup>2</sup> UES\*ppm\*hours), yarn manufacturing (1378.1 m<sup>2</sup> UES\*ppm\*hours), transport of yarn (165.9 m<sup>2</sup> UES\*ppm\*hours), knitting (520.13 m<sup>2</sup>

UES\*ppm\*hours), T-shirt making-up (176.02 m<sup>2</sup> UES\*ppm\*hours) and disposal (981.21 m<sup>2</sup> UES\*ppm\*hours) are insignificant considering whole stages of life cycles (Figures 4.20 - 4.23 and Table B.13).

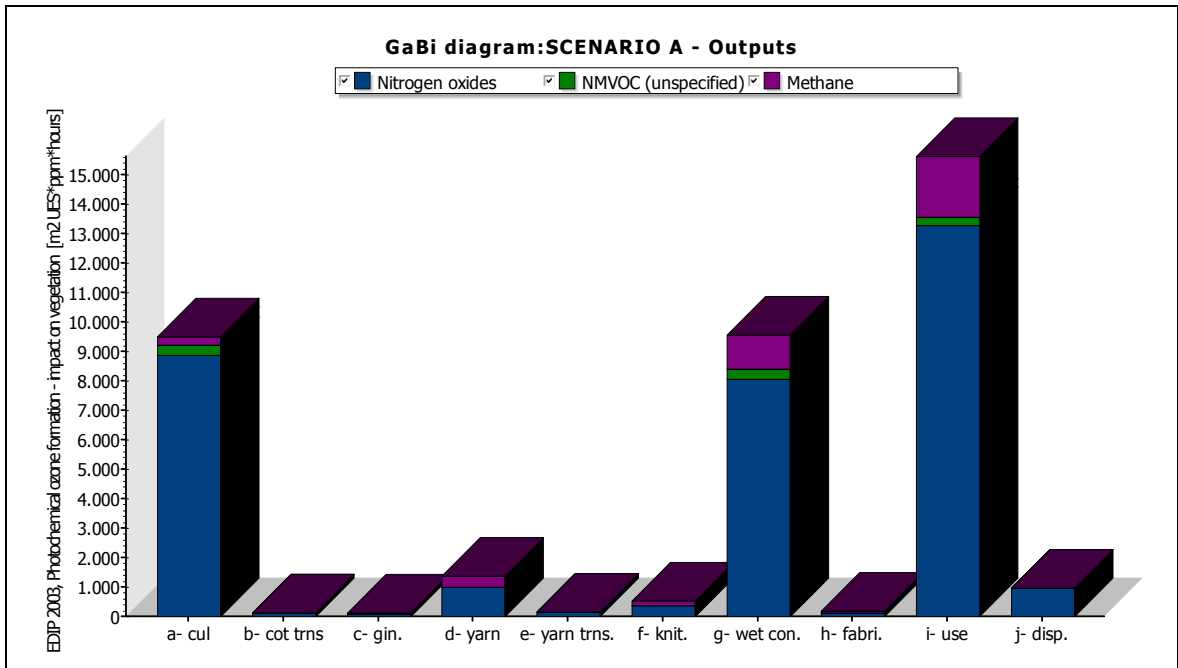


Figure 4.20. POFP - impact on vegetation for scenario A.

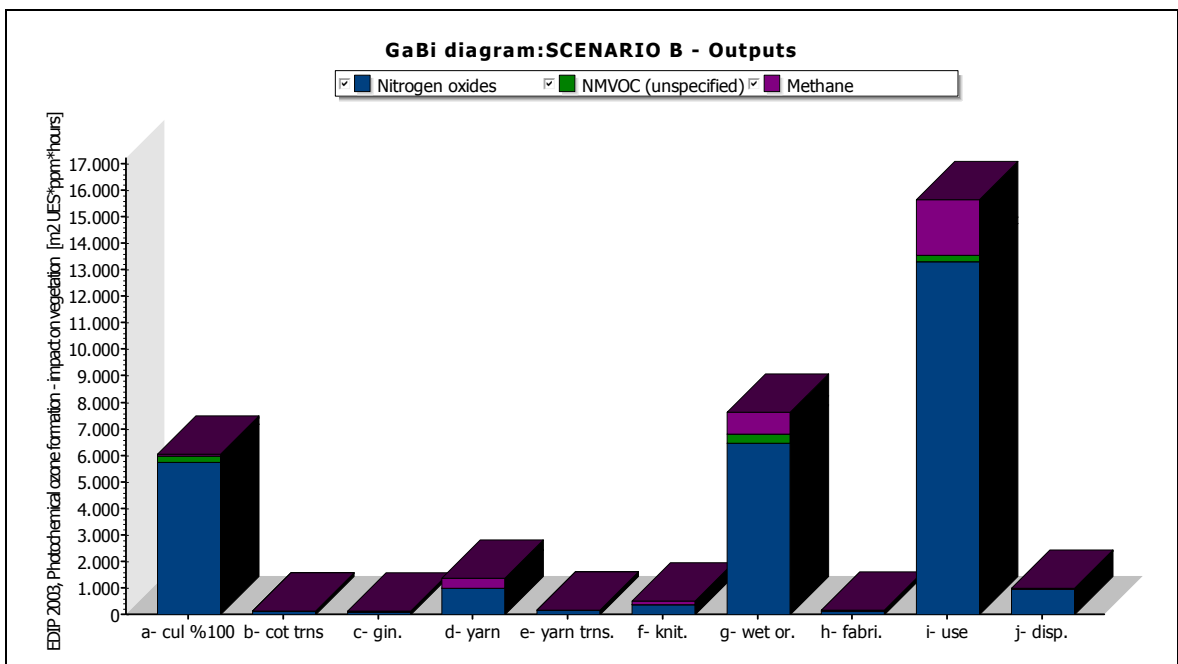


Figure 4.21. POFP - impact on vegetation for scenario B.

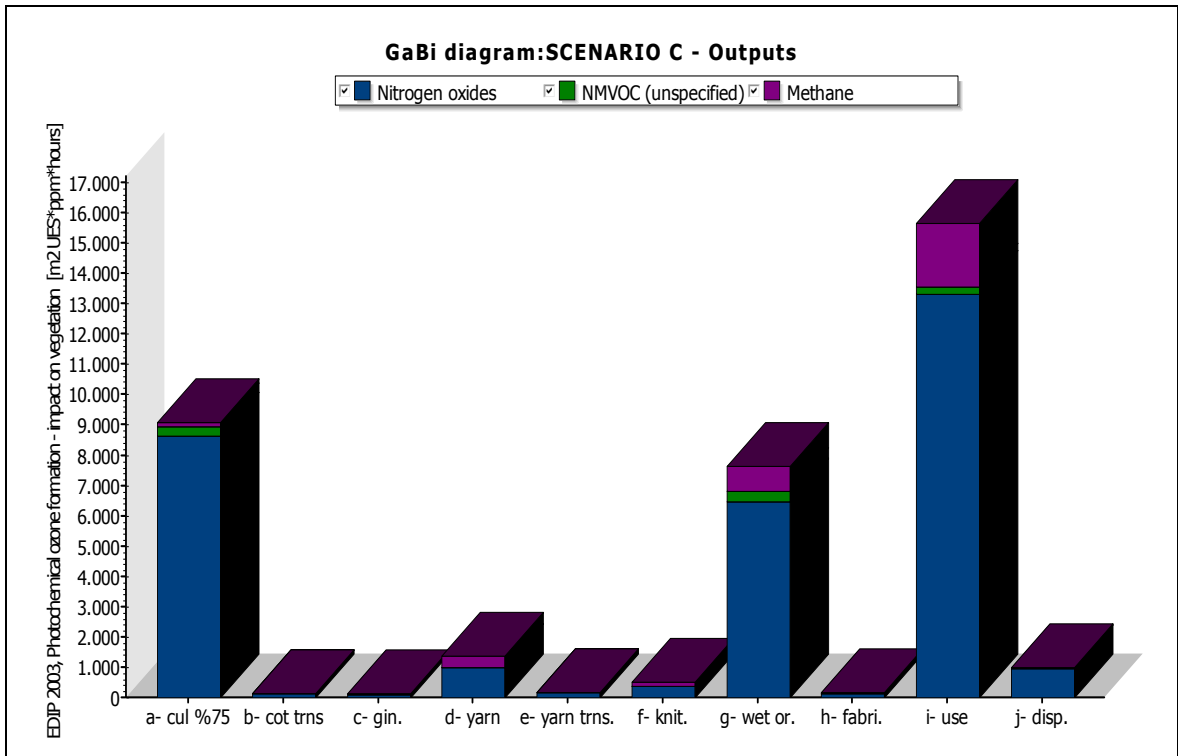


Figure 4.22. POFP - impact on vegetation for scenario C.

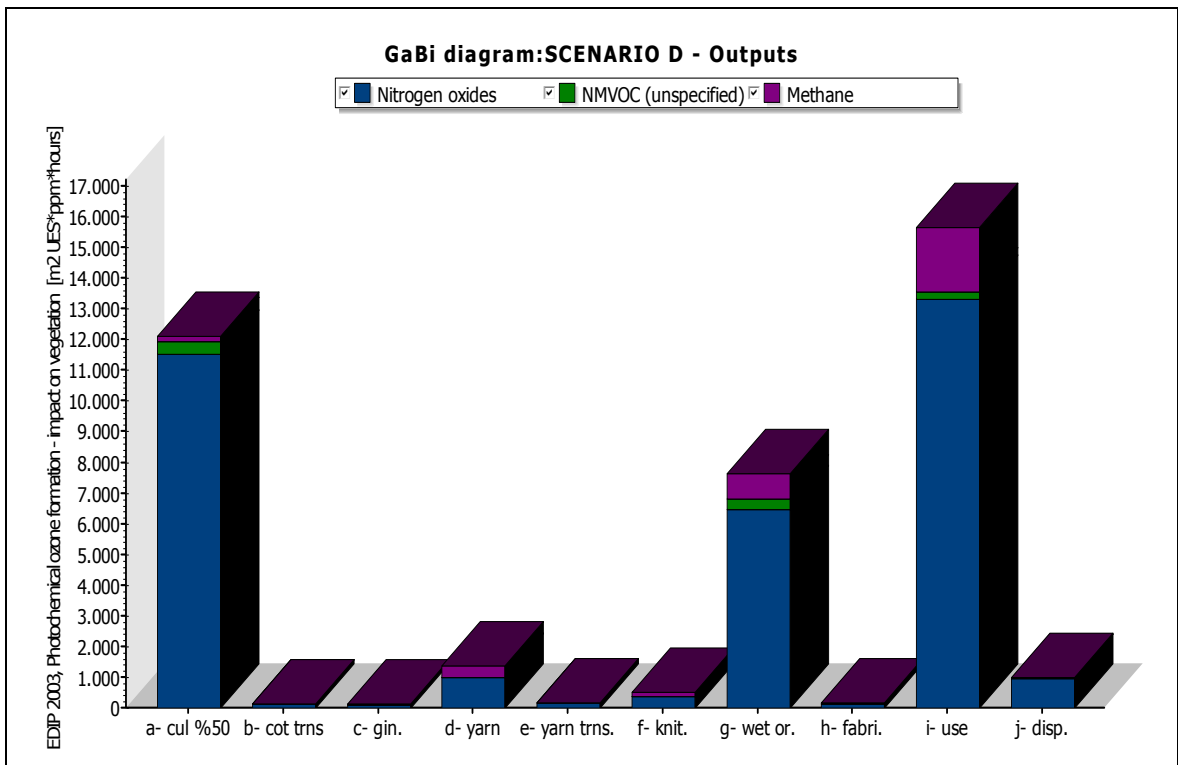


Figure 4.23. POFP - impact on vegetation for scenario D.

## 4.2. Normalization

Mainly there are two general goals in normalization. Firstly, it supports the software user in having an impression of the relative scaling of the calculated impact potentials. However, normalization gives limited information about the importance and seriousness of environmental impacts of the LCA system, considering the geographical area where the activities in the LCA occur. Secondly, it leads to the individual impacts to be combined into a dimensionless final score in a form suitable for weighting to compare all environmental impacts using the same scale. Scores obtained in the normalization are assessed according to importance of impact potentials at the next section called weighting.

For the global impact categories, whole world is influenced; thus a reference to the whole world is utilized. Regional and local environmental impacts only take into account the region or local area where the impact occurs. The methodology utilizes the population of people in the region for which the impact is evaluated. The normalized potentials are fractions of the impact from an average person's contribution to the total and expressed as person-equivalent. In Figure 4.24 normalization references and weighting factors according to EDIP2003 are illustrated. GaBi4 calculates the normalized impact potentials (NEP) according to EDIP2003 factors using the Equation 2.2.

Quantity	Equivalences	Unit	Standard	Weights
EDIP 2003, Acidification potential	0,7874	m2 UES	0 %	1,27
EDIP 2003, Aquatic eutrophication	0,81967	kg NO3-Equ	0 %	1,22
EDIP 2003, Global warming	0,89286	kg CO2-Equ	0 %	1,12
EDIP 2003, Photochemical ozone formation - impact	0,75188	pers*ppm	0 %	1,33
EDIP 2003, Photochemical ozone formation - impact	0,75188	m2 UES*ppr	0 %	1,33
EDIP 2003, Stratospheric ozone depletion	0,015873	kg R11-Equi	0 %	63
EDIP 2003, Terrestrial eutrophication	0,81967	m2 UES	0 %	1,22

Quantity	Equivalences	Unit	Standard	Weights
EDIP 2003, Acidification potential	2200	m2 UES	0 %	0,00045455
EDIP 2003, Aquatic eutrophication	58	kg NO3-E	0 %	0,017241
EDIP 2003, Global warming	8700	kg CO2-E	0 %	0,00011494
EDIP 2003, Photochemical ozone formation - impact	10	pers*ppm	0 %	0,1
EDIP 2003, Photochemical ozone formation - impact	1,4E005	m2 UES	0 %	7,1429E-00
EDIP 2003, Stratospheric ozone depletion	0,103	kg R11-E	0 %	9,7087
EDIP 2003, Terrestrial eutrophication	2100	m2 UES	0 %	0,00047619

Figure 4.24. Normalization references and weighting factors for EDIP2003

The sum of each category indicator result is divided by a normalization reference value to calculate NEP. The calculation of normalized global warming and aquatic eutrophication scores for scenario A are exemplified below:

The potential impact of 1000 pieces of conventional T-shirt over its lifetime to GWP is 9091.3 kg CO<sub>2</sub>-eq and AEP is 56.627 kg NO<sub>3</sub><sup>-</sup>-eq. The average person (world) contributes to GWP 8700 kg of CO<sub>2</sub>- eq per year and the average person (European) contributes to AEP 58 kg NO<sub>3</sub><sup>-</sup>-eq per year. Using Eq (2.2), the NEP<sub>(global warming)</sub> and NEP<sub>(aquatic eutrophication)</sub> can be found:

$$\begin{aligned} \text{NEP}_{(\text{global warming})} &= 9091.3 \text{ kg CO}_2\text{-eq} / 8700 \text{ kg CO}_2\text{-eq} \\ &= 1.045 \end{aligned}$$

$$\begin{aligned} \text{NEP}_{(\text{aquatic eutrophication})} &= 56.627 \text{ kg NO}_3^-\text{-eq} / 58 \text{ kg NO}_3\text{-eq} \\ &= 0.976 \end{aligned}$$

These values correspond to 104.5% and 97.6% of a person's annual contribution to global warming and aquatic eutrophication respectively.

Normalization scores are calculated for the impact categories depletion of global warming, photochemical ozone formation-impact on vegetation, acidification, aquatic eutrophication, and terrestrial eutrophication using European territory and the world in 1990 and 1995 as reference situations for all investigated scenarios as given in Figure 4.25.

Within the frame of LCA, normalization provided information on which contributions are, in relation to each other, small or large. The significant issues of life cycle of conventional T-shirt representing scenario A are the global warming, followed by aquatic eutrophication potential. The percent contributions of normalized impact values of global warming and aquatic eutrophication in scenario A are 37.27% and 34.80% respectively. In addition to these, the percent contributions of normalized impact values of terrestrial eutrophication, photochemical ozone formation and acidification are 12%, 9.73% and 6.16% respectively (Figure 4.25 and Table B.16).

Considering ECO T-shirt representing scenarios B, C and D, which differs from each other from the point of agricultural productivity only, normalization scores for are mostly dominated by global warming with a share of 51.3%, 49.93%, 48.63% respectively. For photochemical ozone formation, aquatic eutrophication, terrestrial eutrophication, and acidification, NEP also appears to be similar with the life cycle of conventional T-shirt (Figure 4.25 and Table B.16).

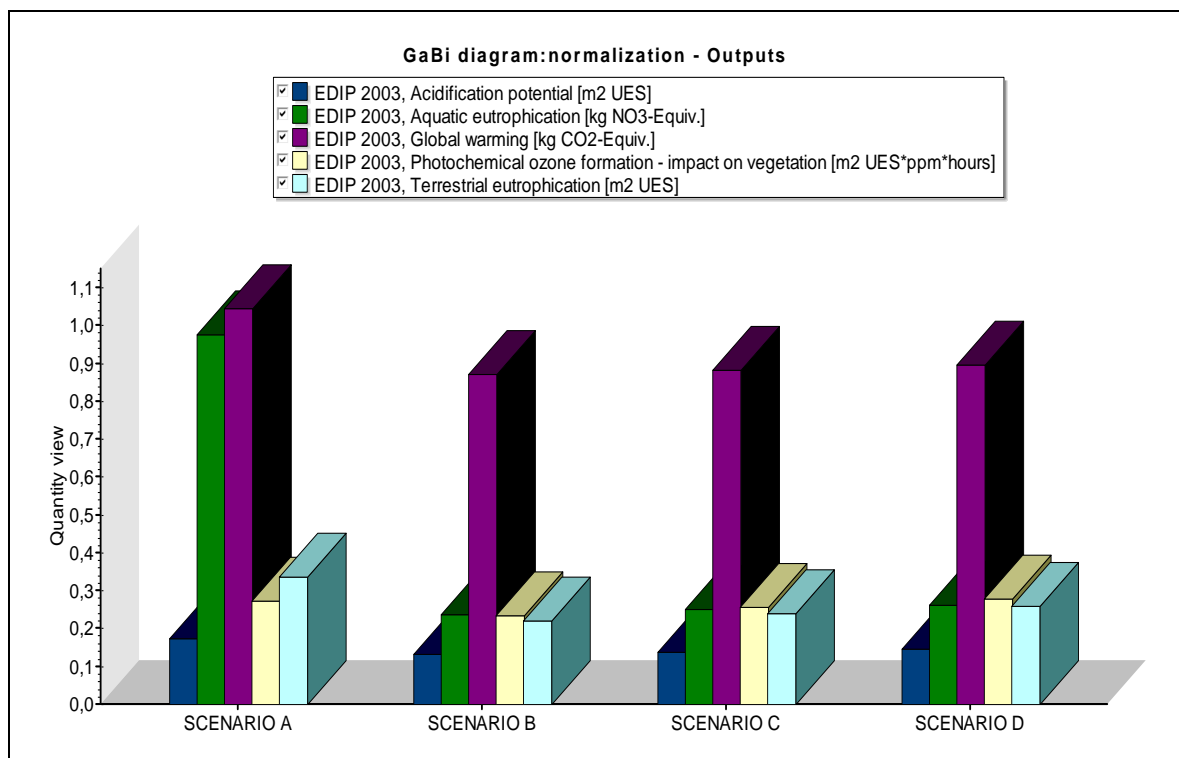


Figure 4.25. NEP for all scenarios.

### 4.3. Weighting

Weighting means an evaluation of the different environmental impacts according to their potential to harm the environment. In other words, weighting determines which potential impacts are more important than the others. The weighting is essential to conclude on the overall environmental performance of products or processes under investigation. The normalization score only reveals the effects within each impact category in relative terms. The final evaluation is obtained by multiplying the normalized impact scores with the respective weighting factor for each impact category. Weighting factors are

determined by a method called distance to target, a ratio between actual impact and a target impact. In order to calculate the weighting factor in EDIP2003 impact evaluation methodology environmental impact potential of the emissions in the reference year 1990-1995 divided by the environmental impact potential of the target emissions in the year 2000. It expresses how much the normalization reference must be reduced by targets.

The flexibility of the EDIP2003 methodology enables small and large-scale impact assessments to be made at various levels of complexity. Depending on the application of the LCA, the criteria for assessment will differ. The EDIP2003 methodology applies weighting factors on the basis of political environmental targets set by the Danish Government or by various international protocols. GaBi4 calculates the weighted impact potentials (WEP) according to EDIP2003 factors using the Eq 2.3.

Weighting factor for global warming is 1.12 and for aquatic eutrophication equals to 1.22. For the NEP of 1.045 global warming and 0.976 of aquatic eutrophication for scenario A, WEP calculated according to approach from Eq (2.3) are as follows:

$$\begin{aligned} \text{WEP}_{(\text{global warming})} &= 1.045 * 1.12 \\ &= 1.1707 \end{aligned}$$

$$\begin{aligned} \text{WEP}_{(\text{aquatic eutrophication})} &= 0.976 * 1.22 \\ &= 1.1907 \end{aligned}$$

Results indicated required reduction to achieve political and scientific targets for the year of 2000.

The weighted results presented in Figure 4.26 and Table B.17 reflect impact evaluation for all scenarios in system boundary. When the life cycle of conventional T-shirt (Scenario A) compared with the life cycle of ECO T-shirt variants (Scenarios B, C and D) it can be seen that there is a net reduction for all impact categories and environmental indicators. In addition to this, Figure 4.27 illustrates effective contributors released during whole life cycles of products.

According to results of study, total WEP of scenario A representing life cycle of conventional T-shirt, aquatic eutrophication (1.1911) and global warming (1.1707) impacts are observed to have the potentials to cause the most serious impacts. Conventional cotton cultivation stage is accounting for 77% of total aquatic eutrophication potential which is mainly caused by application of N fertilizers. In detail, the contribution of  $\text{NO}_3^-$  emissions to water constitutes 80% of total, whereas  $\text{NH}_3$  to air and  $\text{PO}_4^{-3}$  to water are less significant.

Taking into account to global warming (1.1707), approximately 77.6% of the total score is resulted from sum of wet processing and use stages mostly associated with wastewater treatment. Moreover,  $\text{CO}_2$  emissions are strongly marked as the most effective emissions.

Weighted impact of global warming is followed by terrestrial eutrophication which is about 0.4113. The weighted impact resulting from the cultivation and harvesting stage, and use stage dominate over other life cycle stages.  $\text{NH}_3$  and  $\text{NO}_x$  emissions almost equally contribute to weighted impact scores for terrestrial eutrophication, where  $\text{NO}_x$  appeared to have slightly higher impact.

Weighted impact score of photochemical ozone formation-impact on vegetation is about 0.3630 which contributes only 10.8% of the total weighted impact. It is observed to be highest in the cotton cultivation and harvesting stage, and use stage which almost equally contribute to impact category resulting mainly from  $\text{NO}_x$ .

Evaluated final impact category is acidification (0.2196). It comprises of 6.5% of total impact. The most effective stages are use and cotton cultivation and harvesting stage with a share of 41.9% and 27.5% respectively.  $\text{SO}_2$  is observed to be most important contributor when it is compared with of  $\text{NH}_3$  and  $\text{NO}_x$ .

Results of WEP of scenarios B, C and D only vary in agricultural productivity. Global warming has the highest score in all three scenarios. Weighted global warming impact potential contributed 48.4% of total for scenario B, 47% of total for scenario C and 45.7% of total for scenario D mostly in connection with use stage and wet processing. Similar

with the scenario A, CO<sub>2</sub> emissions to air are responsible for the scores of weighted global warming impact. Comparing scenarios B, C and D among each other, twenty-five percent decrease in productivity rate resulted in 1.5 percent increase in the impact potential.

The second adverse impact is found as photochemical ozone formation-impact on vegetation which has weights of around 0.3111, 0.3406 and 0.3693 for scenarios B, C and D respectively (Figure 4.26). It is observed to be highest in the cotton cultivation and harvesting stage, and use stage caused mainly by NO<sub>x</sub> release.

Regarding total weighted impact, aquatic eutrophication is ranking third in terms of impact magnitude. Calculations indicate that weighted impact of aquatic eutrophication for scenario B (0.2903), scenario C (0.3057) and scenario D (0.3211) change by 5% - 25% decrease in agricultural productivity. It is also found that particularly use stage in connection with NO<sub>3</sub><sup>-</sup> and NO<sub>x</sub> emissions are significant.

Terrestrial eutrophication is found to be important for scenario B (0.2693), scenario C (0.2933) and scenario D (0.3172) following to aquatic eutrophication. The share of organic cotton cultivation and harvesting, and use stage over other life cycle stages is remarkably higher for ECO-Tshirt scenarios.

Similar with the scenario A representing life cycle of conventional T-shirt, acidification potential for life cycle of ECO T-shirt is found to have the lowest impact among other impact categories. Measured impact values are 0.1668, 0.1754 and 0.1840 for scenarios B, C and D respectively. SO<sub>2</sub> and NO<sub>x</sub> are observed to be the most important contributors when they are compared with of NH<sub>3</sub>.

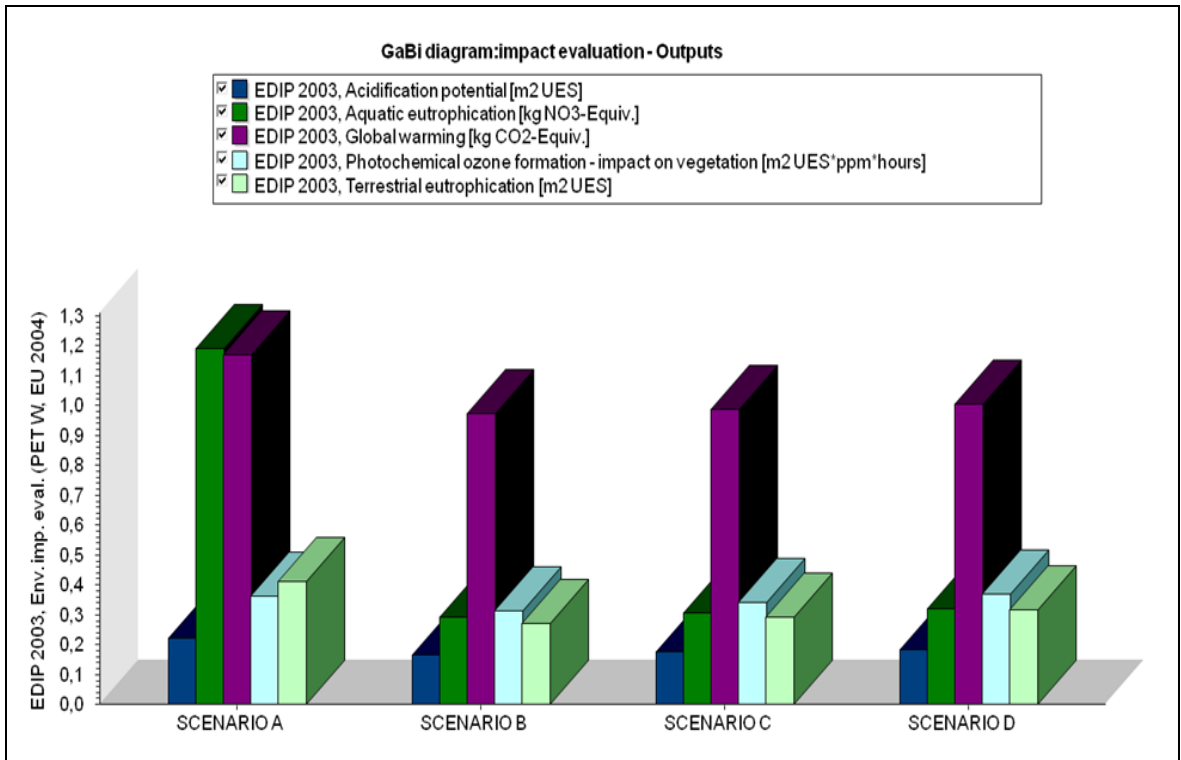


Figure 4.26. WEP for all scenarios.

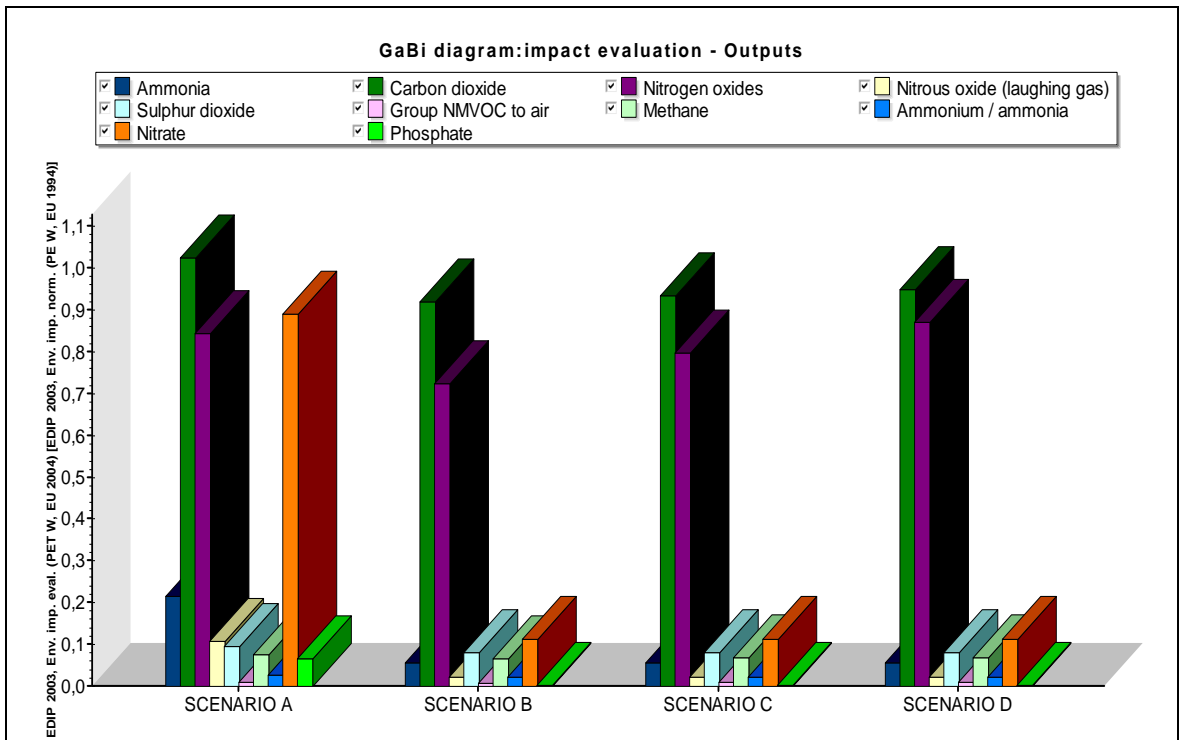


Figure 4.27. Detailed WEP for all scenarios.

## 5. CONCLUSIONS

This study analyzes and compares the environmental impacts of conventional T-shirt and ECO T-shirt variants for four different life cycle scenarios using LCA with EDIP2003 assessment methodology. Environmental impact categories considered in this study are acidification, aquatic eutrophication, terrestrial eutrophication, photochemical ozone formation (impact on vegetation) and global warming. Overall normalized and weighted environmental impacts are also obtained and presented. Life cycle stages of the T-shirt included in the analysis are cultivation and harvesting for raw material supply, ginning, spinning, knitting, wet fabric processing, service/use and disposal stages. All impacts are analyzed and presented on 1000 items of knitted and dyed cotton T-shirt basis with a total weight of 200 kg and a life span of 3 years covering 50 times washing at a temperature of 60 °C without prewash application. Products are evaluated on stage-by-stage and overall basis. Based on LCI and LCIA, the following findings emphasize the main results of study.

Raw material supply is the main life cycle stage that on average constitutes around 42% of the overall environmental impact of Conventional T-shirts. The result of analysis revealed that major reductions across all environmental impact categories are observed when switching from conventional to organic cotton cultivation. Decrease in environmental impacts is mainly associated with biological processes applied to maintain soil fertility, and natural insect, weed and diseases control. An additional benefit of organic cultivation is to reduce diesel consumption by farm machinery used for fertilizer and pesticide application. Moreover, comparing the ECO T-shirt scenarios B, C and D, with agricultural productivity rates of 100%, 75% and 50% show an increase in all impact potentials in the range of 50-100% due to larger agricultural area requirement which results in higher diesel consumption by the machinery operating in the field. Application of more sustainable fiber production methodology has decreased the environmental impact potentials of the raw material supply stage between the ranges of 63.1 – 81.6% for global warming, 42.85 – 71.4% for acidification, 93.3 – 96.65% for aquatic eutrophication, 45.85 - 72.9% for terrestrial eutrophication and finally 4.5 – 36.4% for photochemical ozone formation.

Ginning stage which has 0.18% overall weighted impact in Conventional T-shirt and 0.28 – 0.31% impact in ECO T-shirt life cycle is considered to have a minor impact in the overall life cycle of the products due to low energy consumption used for per functional unit (759.55 MJ). However, according to LCI results, this stage has a large impact in terms of bulk waste production with 65% waste production per unit mass input.

According to inventory analysis, yarn manufacturing stage covering seven different sub-stages is ranking second in terms of energy consumption used for per functional unit (3,131.75MJ). All impacts from this stage result from electric power consumption with 3.45% and 5.28–5.75% overall weighted impacts for Conventional and ECO T-shirts, respectively. Moreover, 7% material loss in the form of a solid waste and dust at different sub-stages of yarn manufacturing is another important environmental aspect of this stage.

Knitting stage has only 1.3% and 2–2.1% share in overall weighted impact of Conventional and ECO T-shirt life cycles due to relatively low electrical energy consumption compared to energy-intensive processes such as yarn manufacturing and use. Waste generation parameter is also lower compared to ginning and yarn manufacturing with only 3% waste generation per unit mass input.

Particularly for the wet processing stage, total environmental weighted impact are determined to be 17.56% for Conventional T-shirt and 21–23% for ECO T-shirt life cycle. Applied CP options for ECO T-shirt production resulted in a considerable amount of water conservation (40%) which is vitally important due to the nature of textile industry. Additionally, 8.5% reduction in kg chemical consumption and 39.5% energy saving per functional unit manufactured is also accomplished through CP. Chemical substitution in bleaching and washing stages and corresponding elimination of several baths in green dyeing recipe has resulted in considerable energy, chemical and water savings from this stage. Moreover, CP applied for ECO T-shirt production has lead to reduction in pollution load of wastewater with a rate of 16% in kg COD. Switching from conventional bleaching to green dyeing recipe caused a net reduction in all investigated impact categories; 22.7% reduction in global warming, 20.35% in acidification, 21.31% in aquatic eutrophication, 19.5% in terrestrial eutrophication and 20.1% in photochemical ozone formation impact potential.

T-Shirt making stage constitutes 0.45% and 0.67-0.73% of the overall weighted impact of Conventional and ECO T-shirt life cycles, respectively, only due to electrical energy input. Bulk waste of fabric remnant generated during fabrication (10%) is significant environmental aspect of the stage.

Consumer use stage has the highest impact across all impact categories and for all scenarios considered in the study. This stage poses nearly half of total impact potentials of acidification, aquatic eutrophication, terrestrial eutrophication, photochemical ozone formation and global warming. It is also the most resource consuming stage among other life cycle stages, particularly in terms of water consumption. The impacts result mainly from electric power consumption (22.7%) and detergent use (23.3%). The percentage of overall weighted impact of this stage in Conventional and ECO T-shirt scenarios are 33% and 50-55%, respectively.

Disposal stage covering incineration of 1000 items of T-shirts, constitutes 2.1% and 3.3-3.6%, of the overall weighted impact potentials of Conventional and ECO T-shirt life cycles, respectively.

Within the scope of the presented study, cultivation applications were adjusted to reflect the conditions of Turkey which ranks seventh in conventional cotton cultivation and third in organic cotton cultivation in the world. Moreover, for wet processing a textile plant located in Hadımköy, İstanbul was investigated for CP option generation and applications. Evaluated source and multi-dimensional decision making points that form the inventory of the yarn manufacturing used in the study were also adopted to conditions of Turkey. Considering the use stage, data related to washing conditions were supplied by a multinational detergent company operating in Turkey. Other life cycle stages which no local data was available were replaced with past data declared. It has also been concluded that consumer can influence the environmental profile through choice of more sustainable products. However, this LCA is not construed as a validation of any production strategy, but rather as a mechanism to evaluate different production and consumption strategies with the intent of improving knowledge and efficiency in terms of environmental consequences of products.

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## **APPENDIX A**

### **Inventory Table for Investigated Scenarios**

Table A.1. Inventory table for all scenarios (continued on the next page).

Life cycle stage	Input/Output Values		Product			
			Conventional T-shirt	ECO T-shirt		
			Scenario A	Scenario B	Scenario C	Scenario D
	Material	Unit	Amount	Amount	Amount	Amount
a- Cotton Cultivation	<b>INPUTS</b>					
	Cotton seed	kg	14.880	14.880	22.320	29,760
	Diesel	kg	63.700	55.510	83.265	111.020
	Water	m <sup>3</sup>	1,665.000	1,665.000	2,497.500	3,330.000
	<b>Auxiliary Chemicals</b>					
	N Fertilizer	kg	66.960			
	P Fertilizer	kg	18.600			
	K Fertilizer	kg	18.600			
	Insecticide	kg	1.607			
	Herbicide	kg	0.946			
	Fungicide	kg	0.049			
	<b>OUTPUTS</b>					
	Seed-cotton	kg	771.480	771.480	771.480	771.480
	<b>Bulk waste</b>					
	Harvest residues	kg	1,542.900	1,542.900	1,542.900	1,542.900
	<b>Emissions to Air</b>					
	CO	kg	0.87767	0.76483	1.1472	1.5297
	CO <sub>2</sub>	kg	202.57	176.520	264.78	353.040
	SO <sub>2</sub>	kg	0.003185	0.0027755	0.0041633	0.00051
	NO <sub>x</sub>	kg	3.2968	2.8729	4.3094	5.7458
	Dust	kg	0.1911	0.16653	0.2498	0.33306
	NMVOC	kg	0.23459	0.20443	0.30664	0.40486
	NH <sub>3</sub> -N	kg	1.3392			
N <sub>2</sub> O-N	kg	0.8202				
<b>Emissions to Water</b>						
NO <sub>3</sub> -N	kg	62.29				
PO <sub>4</sub> -P	kg	0.245				
b- Seed-Cotton Transportation	<b>INPUTS</b>					
	<b>Resource Consumption</b>					
	Diesel	kg	2.4832	2.4832	2.4832	2.4832
	<b>OUTPUTS</b>					
	<b>Emission to air</b>					
	CO	kg	0.014765	0.014765	0.014765	0.014765
	CO <sub>2</sub>	kg	7.8842	7.8842	7.8842	7.8842
	SO <sub>2</sub>	kg	0.00024832	0.00024832	0.00024832	0.00024832
	NO <sub>x</sub>	kg	0.066457	0.066457	0.066457	0.066457
	Dust	kg	0.0017181	0.0017181	0.0017181	0.0017181
	NMVOC	kg	0.0036024	0.0036024	0.0036024	0.0036024
	<b>INPUTS</b>					
	Seed-cotton	kg	771.480	771.480	771.480	771.480
	Polyethylene film	kg	3.235	3.235	3.235	3.235
	<b>Resource Consumption</b>					

Table A.1. (Continued).

<b>c- Ginning</b>	Electric power	MJ	52.339	52.339	52.339	52.339
	LP gas	kg	15.533	15.533	15.533	15.533
	<b>OUTPUTS</b>					
	Cotton lint (fibre)	kg	270.020	270.020	270.020	270.020
	<b>Bulk waste</b>					
	Cotton seed	kg	478.31	478.31	478.31	478.31
	Reclaimed fiber	kg	9.720	9.720	9.720	9.720
	Trash	kg	9.430	9.430	9.430	9.430
	<b>Emission to air</b>					
	Dust	kg	4.000	4.000	4.000	4.000
<b>d- Yarn Manufacturing</b>	<b>INPUTS</b>					
	Cotton lint (fibre)	kg	270.020			
	<b>Resource Consumption</b>					
	Electric power	MJ	3,131.750	3,131.750	3,131.750	3,131.750
	<b>OUTPUTS</b>					
	Cotton-yarn	kg	243.700	243.700	243.700	243.700
	<b>Bulk waste</b>					
	Fiber waste	kg	2.660	2.660	2.660	2.660
	Non-lint trash	kg	3.420	3.420	3.420	3.420
	Sliver	kg	2.780	2.780	2.780	2.780
	Sweeps	kg	10.100	10.100	10.100	10.100
	Polyethylene-film	kg	3.235	3.235	3.235	3.235
	<b>Emission to air</b>					
Dust	kg	7.360	7.360	7.360	7.360	
<b>e- Yarn Transportation</b>	<b>INPUTS</b>					
	<b>Resource Consumption</b>					
	Diesel	kg	3.2311	3.2311	3.2311	3.2311
	<b>OUTPUTS</b>					
	<b>Emission to air</b>					
	CO	kg	0.017722	0.017722	0.017722	0.017722
	CO <sub>2</sub>	kg	10.259	10.259	10.259	10.259
	SO <sub>2</sub>	kg	0.00032311	0.00032311	0.00032311	0.00032311
	NO <sub>x</sub>	kg	0.085485	0.085485	0.085485	0.085485
	Dust	kg	0.0019179	0.0019179	0.0019179	0.0019179
NMVOC	kg	0.0037595	0.0037595	0.0037595	0.0037595	
<b>f- Knitting</b>	<b>INPUTS</b>					
	Cotton-yarn	kg	243.700	243.700	243.700	243.700
	<b>Resource Consumption</b>					
	Electric power	MJ	1,182.000	1,182.000	1,182.000	1,182.000
	<b>OUTPUTS</b>					
	Knitted fabric	kg	236.400	236.400	236.400	236.400
	<b>Bulk waste</b>					
	Fabric remnant	kg	5.840	5.840	5.840	5.840
	<b>Emission to air</b>					
Dust	kg	1.460	1.460	1.460	1.460	
	<b>INPUTS</b>					
	Knitted fabric	kg	236.400	236.400	236.400	236.400
	<b>Resource Consumption</b>					
	Electric power	MJ	608.135	447.995	447.995	447.995
	Steam	MJ	5,348.848	3,164.468	3,164.468	3,164.468

Table A.1. (Continued).

<b>g- Wet Processing</b>	Water	L	35,460.000	21,276.000	21,276.000	21,276.000
	<b>Auxiliary Chemicals</b>					
	Wetting agent	kg	2.364	2.364	2.364	2.364
	Desizing enzyme	kg	0.709	0.709	0.709	0.709
	Acedic acid	kg	9.456	7.092	7.092	7.092
	Sequestering agent	kg	4.728	2.364	2.364	2.364
	Salt	kg	165.480	165.480	165.480	165.480
	Soda ash	kg	47.280	47.280	47.280	47.280
	Dyestuff	kg	9.766	9.766	9.766	9.766
	Soap	kg	2.364	2.364	2.364	2.364
	Cationic softener	kg	4.728	4.728	4.728	4.728
	Silicon	kg	2.364	2.364	2.364	2.364
	Anticrease agent	kg	2.364			
	Caustic	kg	5.910			
	Hydrogen peroxide	kg	5.910			
	Oil removing agent	kg	1.182			
	Stabilizer	kg	1.182			
	Sodyum thiosulphate	kg	2.364			
	<b>OUTPUTS</b>					
	Dyed fabric	kg	222.220	222.220	222.220	222.220
	<b>Bulk waste</b>					
Fabric remnant	kg	14.180	14.180	14.180	14.180	
Wastewater	L	35,171.000	20,987.000	20,987.000	20,987.000	
<b>Emissions to Water</b>						
COD	kg	46.06	38.74	38.74	38.74	
<b>h- T-shirt Production</b>	<b>INPUTS</b>					
	Dyed fabric	kg	222.220	222.220	222.220	
	<b>Resource Consumption</b>					
	Electric power	MJ	400.000	400.000	400.000	
	<b>OUTPUTS</b>					
	1000 items T-shirts	kg	200.000	200.000	200.000	
	<b>Bulk waste</b>					
Fabric remnant	kg	22.220	22.220	22.220		
<b>i- Use</b>	<b>INPUTS</b>					
	1000 items T-shirts	kg	200.000	200.000	200.000	
	<b>Resource Consumption</b>					
	Electric power	MJ	6,838.900	6,838.900	6,838.900	
	Water	L	81,665.000	81,665.000	81,665.000	
	<b>Auxiliary Chemicals</b>					
	Detergent	kg	375.000	375.000	375.000	
	<b>OUTPUTS</b>					
1000 items T-shirts	kg	200.000	200.000	200.000		
Wastewater	L	81,545.000	81,545.000	81,545.000		
	<b>INPUT</b>					
	1000 items T-shirts	kg	200.000	200.000	200.000	
	<b>Resource Consumption</b>					

Table A.1. (Continued).

<b>j- Disposal</b>	Diesel	kg	0.70711	0.70711	0.70711	0.70711
	<b>OUTPUTS</b>					
	<b>Emission to air</b>					
	CO	kg	0.00096	0.00096	0.00096	0.00096
	CO <sub>2</sub>	kg	0.56127	0.56127	0.56127	0.56127
	NO <sub>x</sub>	kg	0.04672	0.04672	0.04672	0.04672
	Dust	kg	0.00010	0.00010	0.00010	0.00010
	NMVOC	kg	0.00020	0.00020	0.00020	0.00020
	Power	MJ	191.980	191.980	191.980	191.980
	Steam	MJ	2,029.900	2,029.900	2,029.900	2,029.900

## **APPENDIX B**

### **Tables for Characterization, Normalization and Weighting Results**

Table B.1. Stage by stage GWP comparison of life cycle scenarios.

Life cycle stages	GWP (kg CO <sub>2</sub> - eq)			
	Scenario A	Scenario B	Scenario C	Scenario D
A- Cultivation and harvesting	1194.8	219.90	329.90	439.90
B- Seed-cotton transportation	8.8917	8.8917	8.8917	8.8917
C- Ginning	22.189	22.189	22.189	22.189
D- Yarn production	617.41	617.41	617.41	617.41
E- Yarn transportation	11.552	11.552	11.552	11.552
F- Knitting	233.02	233.02	233.02	233.02
G- Wet processing	2420.7	1872.2	1872.2	1872.2
H- T-shirt making-up	78.857	78.857	78.857	78.857
I- Use	4140.4	4140.4	4140.4	4140.4
J- Disposal	363.53	363.53	363.53	363.53
Total	9091.3	7567.9	7677.9	7787.9

Table B.2. Comparison of GWP for sub-processes of cotton cultivation.

Cultivation and harvesting sub-processes	GWP (kg CO <sub>2</sub> -eq)			
	A	B	C	D
Energy generation	227.6	198.3	297.3	396.7
Pesticide production	13.70	-	-	-
Fertilizer production	669.4	-	-	-
Fertilizer consumption	262.5	-	-	-
Cotton seed-production	5.100	5.100	7.700	10.20
Irrigating	16.50	16.50	24.70	33.00
Total	1194.8	219.9	329.9	439.9

Table B.3. Comparison of GWP for sub-processes of wet processing.

Wet processing sub-processes		GWP (kg CO <sub>2</sub> -eq)			
		A	B	C	D
Wet process	Energy generation	478.21	300.31	300.31	300.31
	Chemical production	216.11	175.36	175.36	175.36
	Softened water	0.8764	0.5258	0.5258	0.5258
Wastewater treatment	Energy generation	141.13	113.83	113.83	113.83
	Chemical production	27.251	16.351	16.351	16.351
	Sludge incineration	1466.6	1186.6	1186.6	1186,6
	Direct emissions	90.519	79.219	79.219	79,219
Total		2420.7	1872.2	1872.2	1872.2

Table B.4. Stage by stage AP comparison of life cycle scenarios.

Life cycle stages	AP (m <sup>2</sup> UES)			
	Scenario A	Scenario B	Scenario C	Scenario D
a- Cultivation and harvesting	104.3	29.80	44.70	59.60
b- Seed-cotton transportation	0.668	0.668	0.668	0.668
c- Ginning	1.427	1.427	1.427	1.427
d- Yarn production	16.40	16.40	16.40	16.40
e- Yarn transportation	0.860	0.860	0.860	0.860
f- Knitting	6.190	6.190	6.190	6.190
g- Wet processing	83.56	66.55	66.55	66.55
h- T-shirt making-up	2.094	2.094	2.094	2.094
i- Use	159.5	159.5	159.5	159.5
j- Disposal	5.502	5.502	5.502	5.502
Total	380.5	289.0	303.9	318.8

Table B.5. Comparison of AP for sub-processes of cotton cultivation.

Cultivation and harvesting sub-processes	AP (m <sup>2</sup> UES)			
	A	B	C	D
Energy for machinery	30.74	26.78	40.17	53.57
Pesticide production	1.223	-	-	-
Fertilizer production	38.40	-	-	-
Fertilizer consumption	30.93	-	-	-
Cotton seed-production	0.623	0.623	0.935	1.247
Irrigating	2.382	2.382	3.594	4.792
Total	104.3	29.80	44.70	59.60

Table B.6. Comparison of AP for sub-processes of wet processing.

Wet processing sub-processes		AP (m <sup>2</sup> UES)			
		A	B	C	D
Wet process	Energy generation	7.595	4.955	4.955	4,955
	Chemical production	15.95	13.12	13.12	13,12
	Softened water	0.037	0.022	0.022	0,022
Wastewater treatment	Energy generation	13.96	11.27	11.27	11,27
	Chemical production	2.355	1.413	1.413	1,413
	Sludge incineration	24.00	19.38	19.38	19,38
	Direct emissions	19.67	16.39	16.39	16,39
Total		83.56	66.55	66.55	66.55

Table B.7. Stage by stage AEP comparison of life cycle scenarios.

Life cycle stages	AEP (kg NO <sub>3</sub> <sup>-</sup> -eq)			
	Scenario A	Scenario B	Scenario C	Scenario D
a- Cultivation and harvesting	43.561	1.4603	2.1904	2.9205
b- Seed-cotton transportation	0.0295	0.0295	0.0295	0.0295
c- Ginning	0.0250	0.0250	0.0250	0.0250
d- Yarn production	0.2626	0.2626	0.2626	0.2626
e- Yarn transportation	0.0380	0.0380	0.0380	0.0380
f- Knitting	0.0991	0.0991	0.0991	0.0991
g- Wet processing	3.3819	2.6612	2.6612	2.6612
h- T-shirt making-up	0.0335	0.0335	0.0335	0.0335
i- Use	8.9529	8.9529	8.9529	8.9529
j- Disposal	0.2432	0.2432	0.2432	0.2432
Total	56.626	13.805	14.535	15.265

Table B.8. Comparison of AEP for sub-processes of cotton cultivation.

Cultivation and harvesting sub-processes	AEP (kg NO <sub>3</sub> <sup>-</sup> -eq)			
	A	B	C	D
Energy generation	1.4440	1.2596	1.8882	2.5177
Pesticide production	0.0119	-	-	-
Fertilizer production	1.7727	-	-	-
Fertilizer consumption	40.132	-	-	-
Cotton seed-production	0.0858	0.0858	0.1288	0.1716
Irrigating	0.1149	0.1149	0.1734	0.2312
Total	43.561	1.4603	2.1904	2.9205

Table B.9. Comparison of AEP for sub-processes of wet processing.

Wet processing sub-processes		AEP (kg NO <sub>3</sub> <sup>-</sup> - eq)			
		A	B	C	D
Wet process	Energy generation	0.1618	0.1031	0.1031	0,1031
	Chemical production	0.4349	0.3914	0.3914	0,3914
	Softened water	0.0008	0.0005	0.0005	0,0005
Wastewater treatment	Energy generation	0.1052	0.0084	0.0084	0,0084
	Chemical production	0.0093	0.0056	0.0056	0,0056
	Sludge incineration	1.1114	0.8665	0.8665	0,8665
	Direct emissions	1.5585	1.2857	1.2857	1,2857
Total		3.3819	2.6612	2.6612	2.6612

Table B.10. Stage by stage TEP comparison of life cycle scenarios.

Life cycle stages	TEP (kg NO <sub>3</sub> <sup>-</sup> - eq)			
	Scenario A	Scenario B	Scenario C	Scenario D
a- Cultivation and harvesting	304.2	82.35	123.5	164.7
b- Seed-cotton transportation	1.740	1.740	1.740	1.740
c- Ginning	1.451	1.451	1.451	1.451
d- Yarn production	14.36	14.36	14.36	14.36
e- Yarn transportation	2.234	2.234	2.234	2.234
f- Knitting	5.422	5.422	5.422	5.422
g- Wet processing	115.4	92.90	92.90	92.90
h- T-shirt making-up	1.835	1.835	1.835	1.835
i- Use	247.1	247.1	247.1	247.1
j- Disposal	14.26	14.26	14.26	14.26
Total	708.0	463.6	504.8	546.0

Table B.11. Comparison of TEP for sub-processes of cotton cultivation.

Cultivation and harvesting sub-processes	TEP (kg NO <sub>3</sub> <sup>-</sup> - eq)			
	A	B	C	D
Energy generation	84.88	74.00	110.9	147.9
Pesticide production	0.740	-	-	-
Fertilizer production	75.03	-	-	-
Fertilizer consumption	135.2	-	-	-
Cotton seed-production	1.580	1.580	2.370	3.160
Irrigating	6.763	6.763	10.20	13.60
Total	304.2	82.35	123.5	164.7

Table B.12. Comparison of TEP for sub-processes of wet processing.

Wet processing sub-processes		TEP (kg NO <sub>3</sub> <sup>-</sup> - eq)			
		A	B	C	D
Wet process	Energy generation	9.283	5.897	5.897	5,897
	Chemical production	17.46	15.31	15.31	15,31
	Softened water	0.049	0.029	0.029	0,029
Wastewater treatment	Energy generation	6.220	5.019	5.019	5,019
	Chemical production	0.540	0.324	0.324	0,324
	Sludge incineration	35.44	28.66	28.66	28,66
	Direct emissions	46.39	37.66	37.66	37,66
Total		115.4	92.90	92.90	92.90

Table B.13. Stage by stage POFP- impact on vegetation comparison of life cycle scenarios.

Life cycle stages	POFP- impact on vegetation (m <sup>2</sup> UES *ppm*hours)			
	Scenario A	Scenario B	Scenario C	Scenario D
a- Cultivation and harvesting	9509.7	6048.1	9072.1	12096
b- Seed-cotton transportation	129.49	129.49	129.49	129.49
c- Ginning	132.79	132.79	132.79	132.79
d- Yarn production	1378.1	1378.1	1378.1	1378.1
e- Yarn transportation	165.90	165.90	165.90	165.90
f- Knitting	520.13	520.13	520.13	520.13
g- Wet processing	9582.5	7656.1	7656.1	7656.1
h- T-shirt making-up	176.02	176.02	176.02	176.02
i- Use	15641	15641	15641	15641
j- Disposal	981.21	981.21	981.21	981.21
Total	38217	32829	35853	38877

Table B.14. Comparison of POFP- impact on vegetation for sub-processes of cotton cultivation.

Cultivation and harvesting sub-processes	POFP- impact on vegetation Potential (m <sup>2</sup> UES *ppm*hours)			
	A	B	C	D
Energy generation	6320.7	5511.1	8262.0	11016
Pesticide production	64.383	-	-	-
Fertilizer production	2587.6	-	-	-
Fertilizer consumption	-	-	-	-
Cotton seed-production	37.429	37.429	56.144	74.858
Irrigating	499.57	499.57	753.89	1005.2
Total	9509.7	6048.1	9072.1	12096

Table B.15. Comparison of POFP- impact on vegetation for sub-processes of wet processing.

Wet processing sub-processes		POFP- impact on vegetation (m <sup>2</sup> UES *ppm*hours)			
		A	B	C	D
Wet process	Energy generation	1023.1	644.15	644.15	644.15
	Chemical production	1669.7	1440.4	1440.4	1440.4
	Softened water	4.1416	2.4849	2.4849	2.4849
Wastewater treatment	Energy generation	533.16	430.28	430.28	430.28
	Chemical production	55.168	33.101	33.101	33.101
	Sludge incineration	2754.1	2227.6	2227.6	2227.6
	Direct emissions	3543.1	2878.1	2878.1	2878.1
Total		9582.5	7656.1	7656.1	7656.1

Table B.16. Side by side NEP comparison of life cycle scenarios.

Impact categories	NEP			
	Scenario A	Scenario B	Scenario C	Scenario D
Global warming	1.045	0.870	0.882	0.895
Acidification	0.172	0.131	0.138	0.144
Aquatic eutrophication	0.976	0.238	0.250	0.263
Terrestrial eutrophication	0.337	0.220	0.240	0.260
Photochemical ozone formation-impact on vegetation	0.272	0.234	0.256	0.277

Table B.17. Side by side WEP comparison of life cycle scenarios.

Impact categories	WEP			
	Scenario A	Scenario B	Scenario C	Scenario D
Global warming	1.1707	0.9746	0.9888	1.0030
Acidification	0.2196	0.1668	0.1754	0.1840
Aquatic eutrophication	1.1911	0.2903	0.3057	0.3211
Terrestrial eutrophication	0.4113	0.2693	0.2933	0.3172
Photochemical ozone formation-impact on vegetation	0.3630	0.3111	0.3406	0.3693