TAMPEREEN TEKNILLINEN YLIOPISTO

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SUSTAINABILITY OF CELLULOSIC FIBRES, AND THEIR PRODUCTION SYSTEMS AND TECHNOLOGIES

Master of Science Thesis

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The examiners of this Master’s thesis has been approved by the Automation, Mechanical and Materials Engineering Faculty Council in its meeting on 12th January 2011

ABSTRACT

TAMPERE UNIVERSITY OF TECHNOLOGY
Master's Degree Programme in Materials Science
BALASUBRAMANIAM, SATHYA PRAKASH: Sustainability of Cellulosic Fibres, and their Production Systems and Technologies
Master of Science Thesis, 80 pages, 13 Appendix pages
November 2011
Major: Fibre, Textile, and Fashion Engineering
Examiners: Prof. Heikki Mattila and Dr. Tech. Marja Rissanen
Keywords: Sustainability indicators, Cellulosic fibre production systems, Viscose (CV), Lyocell (CLY), Cotton (CO), Polyester (PES), Country blocks, Relative sustainability index

The textile industry will face the next biggest challenge after the industrial revolution when the raw materials of the synthetics (non-renewable petrochemicals) start to run off. Considering the fact that about 60.6% of the fibres consumed in 2009 are produced from petrochemical sources, it is clear that a high dependence of the textile industry on crude is very concrete. Cotton, the second largest consumed fibre with around 32% share in the global fibre consumption in 2009, doesn't have a promising future scope for growth. Some of the reasons are its productivity already being affected due to climate change, larger land demand for food and biofuels production, and also land needs for growing population around the world. A solution in the foreseeable future can only be possible with manufactured fibres made from renewable resources like cellulose.

This work is an investigation on the sustainability of the cellulosic fibres' (including cotton) production systems and technologies. The investigation is carried by applying the UN's working list of indicators of sustainable development on the member countries of the United Nations segmented into country blocks in this work. A scoring method has been introduced to quantify the sustainability indicators. The sustainability of viscose and lyocell production systems along with that of cotton and polyester in different country blocks were quantified using the index and compared.

It has been found that Block 1 countries (the developed nations of the world) and Block 2 countries (highly populated and developing nations of the world), as explained in this work, have respectively the most conducive conditions and least conducive conditions to run any fibre production system sustainably. Lyocell is more sustainable than viscose anywhere in the world. However, the sustainability of any cellulosic fibre production system, including Lyocell, can substantially be increased by using wood pulps also from temperate forests. Out of the four fibre production systems cotton seems to be most unsustainable, and polyester seems to be the most sustainable.

PREFACE

This Master's Thesis work is done for Master of Science degree at Tampere University of Technology. I have done this work at the Department of Fibre Materials Science under the supervision of Prof. Heikki Mattila, and research fellow Dr. Tech. Marja Rissanen.

I would like to extend my sincere gratitude especially to Prof. Heikki Mattila and Dr. Tech. Marja Rissanen, and to all those who have helped me in this work.

To a more sustainable world.

Tampere, 01.11.2011

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1. INTRODUCTION

The textile industry faced a lot of challenges during the industrial revolution, when mass production was needed. A lot of inventions and developments following the challenges made the textile industry one of the most dynamic and influential industries for then industrializing economies. In fact the first steam engines were built to power textile industries. The challenges faced from then were with consistent supply of raw material (cotton and wool), powering the industries, mechanizing and optimizing the production, reducing labour need, and trade development. The rise of the petrochemical industry supplied mass amount of cheap polymers which later was engineered to able to be spun and made into textiles. Since the introduction of synthetics to the textile industry, it overcame most of the challenges faced during the industrial revolution.

Textile materials are made of organic raw materials sources like crude petroleum, cellulose, and animal protein sources like hair and milk. A very few exceptional inorganic textiles are made from sources like metal and glass, but they can be used only in the form of fibre blends. Of all the sources mentioned above, animal protein and cellulose are renewable resources, and they only account to 38.6% (cotton = 32%, wool = 1.6%, and regenerated cellulose = 5.0%) of the global fibre production in 2009. A major portion of about 60%, of the global fibre production comes from non-renewable fossil sources. (CIRFS, 2010) This situation seems alarming for the future raw materials supply security for the textile fibre production, when the petroleum production starts to decline.

Peak oil

M. King Hubbert published his classical work "Nuclear Energy and The Fossil Fuels” in 1956 and explained a theory to predict the peak oil, which popularly became known as 'peak oil theory' or 'Hubbert peak theory'. Peak oil is a term used to mark the time when a particular oil production site reaches its highest production rate. It is represented by the tip of a bell shaped curve plotted against time of production and production rate. The curve became popularly known as the Hubbert curve. Peak oil is followed after a period of sharp increase in production rate, after which the curve starts to decline equally sharp and then gradually towards zero, as shown in Figure 1. (Hubbert, 1956)

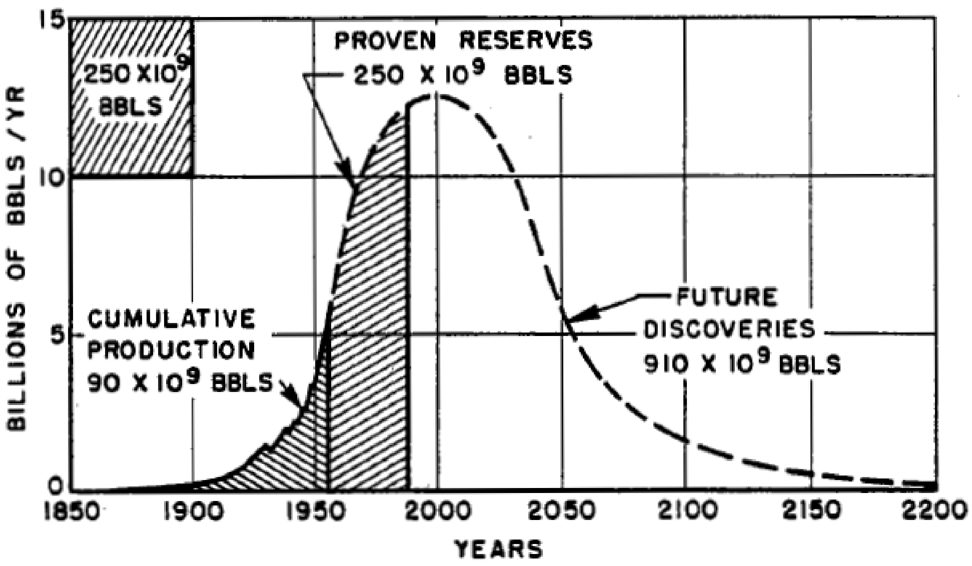

Figure 1 Hubbert's prediction of world peak oil, showing the curve peak in the year 2000. (Hubbert, 1956)

Hubbert predicted peak oil for the world to be around the year 2000. Hubbert's theory was strongly criticized in the US following the publication of his theory, but with time his peak oil predictions were proven very exact for many states in the US. From then on many studies have been made on his theories and many new models have been proposed by different scientists around the world. One such recent model was published by three Kuwaiti researchers in "Forecasting World Crude Oil Production Using Multi Cyclic Hubbert Model" in 2010. The model predicts the peak oil for the world to be during the year 2014, as expressed in Figure 2.(Nashawi, Malallah, & Al-Bisharah, 2010) This is now very commonly believed in the petroleum industry to be the peak oil for the world.

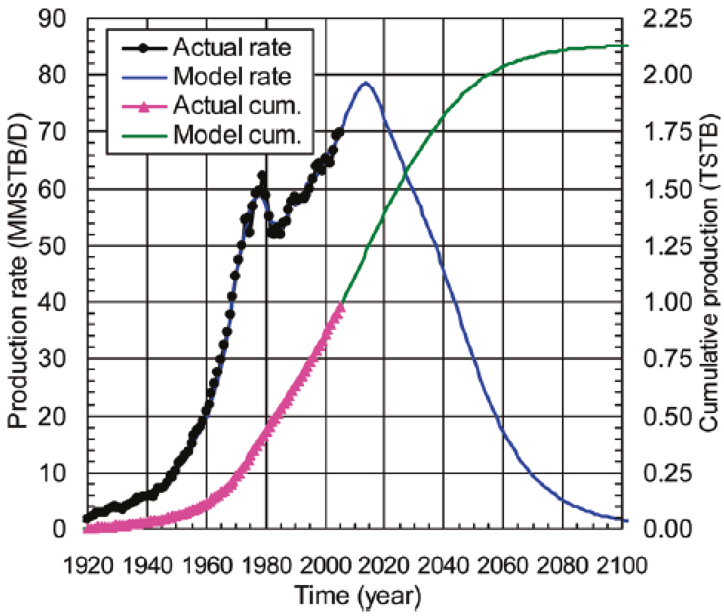

Figure 2 Showing the recent peak oil prediction around 2014. The production rate is expressed by the bell shaped curve in MMSTB/D (million stock tank barrels per day). The cumulative production is expressed in TSTB (trillion stock tank barrels per day). One stock tank barrel/STB = 1 m^3 of oil.(Nashawi, Malallah, & Al-Bisharah, 2010)

Figure 3 and Figure 4 show the increasing dominance of synthetics over other fibres from 1970 till 2009.

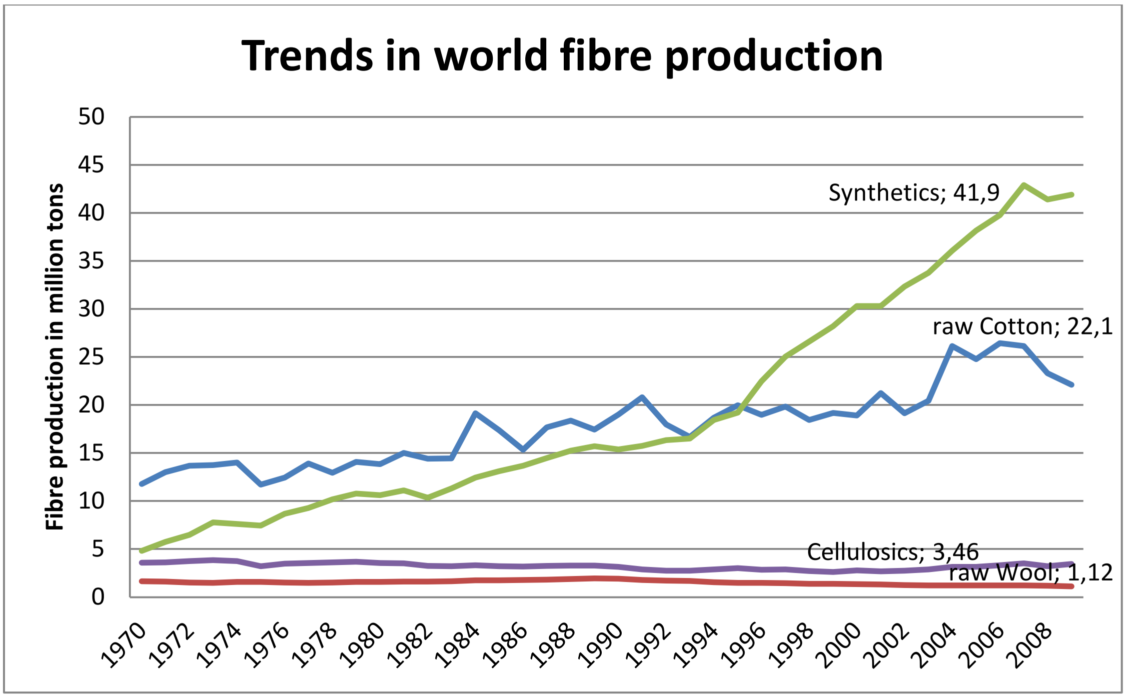

Figure 3 Trends in world fibre production from 1970 to 2009. (CIRFS, 2010)

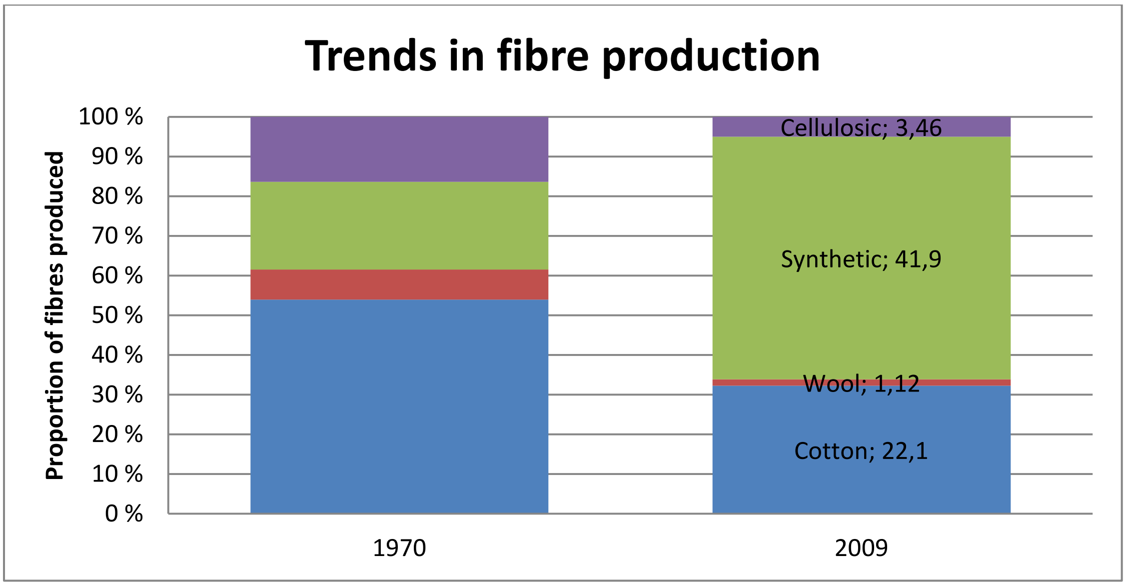

Figure 4 Trends in fibre production during 1970 and 2009. Total productions of different fibres are expressed by numbers written respectively on the chart. (CIRFS, 2010)

What does peak oil mean to the textile industry?

Considering the facts a) both the demands of petroleum and textile fibres are increasing, b) no substitute has yet been developed to satisfy the growing fibre needs, and c) if the predicted peak oil becomes true by the year 2014; the industrial scenario will predictably follow these changes.

- Prices of petroleum and petroleum products will rise, due to their increasing demand and reducing supply. The oil demand for the period from 2009 to 2030 is expected to rise 0.9% on an annual average around the world, out of which, 75% of the demand will come from developing countries. (Griffin, 2010).
- Increasing petroleum prices will also increase the cost of transport of textile goods and also the production costs for textile industries, as expressed in the Figure 5.

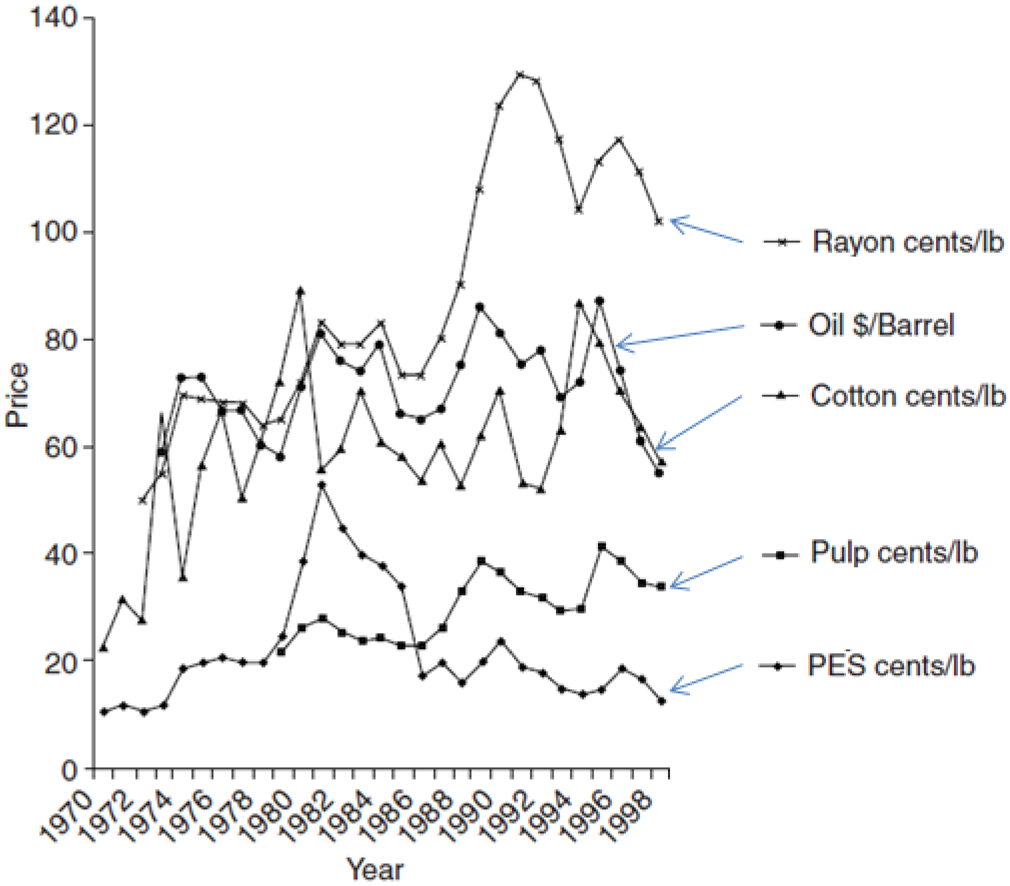

Figure 5 Trends in the prices of oil, pulp, cotton, rayon, and polyester in the USA in US$. (Woodings, Regenerated cellulose fibres, 2001)

- The global population is estimated to increase by 1.4 times by the year 2050 from 2010.(Novartis Foundation, 2010). Increasing population will increase the demand for all consumer goods like textile fibres and petroleum.
- Reduction in petroleum products supply. Which also means the required raw materials for synthetic fibre production like terephthalic acid (for polyester production) will be getting reduced in supply. Also the current supply of NMMO (*N*-Methylmorpholine-*N*-oxide) mostly comes from petroleum sources. NMMO is used as a solvent for cellulose dissolution in the lyocell process.
- Limiting supply of cotton fibres cannot fill the supply and demand gap of the textile fibres in the future. The cotton production in the year 2010 has largely been affected by climate change, which is accountable for the floods and famine in the cotton growing countries like Pakistan and some parts of Africa. World

natural fibre production fell by 5.7% in 2009. And cotton prices have been increasing since March 2009. (Textiles Intelligence, 2010)

The above mentioned reasons will push up the prices of all the current synthetic and natural fibres, until a solution is developed to satisfy the growing fibre needs.

The Copenhagen Accord, agreed by 127 countries in the UNFCCC[i] COP-15[ii] in Copenhagen on December 2009, states in its first point:

"1. We underline that climate change is one of the greatest challenges of our time. We emphasize our strong political will to urgently combat climate change in accordance with the principle of common but differentiated responsibilities and respective capabilities. To achieve the ultimate objective of the Convention to stabilize greenhouse gas concentration in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system, we shall, recognizing the scientific view that the increase in global temperature should be below 2 degrees Celsius, on the basis of equity and in the context of sustainable development, enhance our long-term cooperative action to combat climate change. We recognize the critical impacts of climate change and the potential impacts of response measures on countries particularly vulnerable to its adverse effects and stress the need to establish a comprehensive adaptation programme including international support."(UNFCCC, 2009)

This makes it concrete that the world will desire a sustainable solution burdening less harm to the environment and humankind. The current cotton production system is very unsustainable by considering the following facts: (Kooistra & Termorshuizen, 2006)

- Cotton cultivation consumes 11% of the world's pesticides for its growth on 2.4% of the world's arable land
- About 8% of the world's arable land is abandoned due to former use for intensive cultivation, mostly cotton
- 53% of cotton fields are irrigated, consuming one-sixth of world's fresh water withdrawal
- Estimated water footprint for producing a cotton T-shirt about is about 2000 litres (Hoekstra, Chapagain, Savenije, & Gautam, 2005)

It seems the future raw materials demand for textile fibres can only be satisfied by regenerated natural polymers, like cellulose. Other natural polymers Casein from milk, feather keratin, wheat gluten and soy protein, can be made into fibres (Poole, Church, & Huson, 2009), but are less feasible for high volume production. Cellulose is the most abundant naturally occurring polymer, which comprises of around 40% matter in wood. Cellulose is the only renewable resource that can easily be available and produced to fibres. Cellulose fibres development has to overcome certain technical and environmental challenges in order to satisfy the estimated fibre demand in the future.

This work

The purpose of this work is to investigate the sustainability aspects of major fibre production systems, and to give an introduction to the future scope of regenerated cellulosics. By a fibre production system, it is meant in this work, the series of processes involved in the textile value chain from raw material extraction until fibre production. Most common cellulosic fibre production processes like viscose and lyocell have been considered in this work. I have included cotton and polyester in this work for comparing and referencing purposes.

In the fore part of this work, in the chapter “Sustainability indicators”, I have introduced a set of sustainability indicators chosen from the "UN’s working list of indicators of sustainable development" (Refer Annex 1), which has been applied to different fibre production systems. I have also introduced a scoring method to evaluate the sustainability of a fibre production system using the sustainability indicators explained before. For convenience in understanding and producing this work, the countries of the world has been classified into four country blocks generally based on their developmental status. The scoring method and the classification of country blocks will be explained in “Research methods”. In the later part, I have applied the chosen sustainability indicators to fibre production systems of viscose (CV), lyocell (CLY), cotton (CO) and polyester (PES), in four different country blocks. An overview of the cellulosic fibres' production systems - viscose and lyocell are discussed, proceeding with the applied sustainability analysis.

Many research works has been published on environmental impacts of textile fibre production systems, but a wide sustainability investigation with the future scope in context is still needed. Since the recent years has seen through the financial crisis times and also the coming years to see, a dramatic change in the investment flows for research and development and building new production facilities for textiles. This work, though being very small comparatively, tries to address the changes towards sustainable fibre production systems.

2. SUSTAINABILITY INDICATORS

2.1. An overview

Sustainability has become one of the most used keywords in recent studies. Any development which is sustainable is getting to be the most desirable. 'United Nations Environment and Development Commission' has defined sustainable development as *"a development that can meet the needs of today's world without endangering the ability of future generations to provide their own needs"*[iii]. In this work's context this would imply conservation of non-renewable resources for the future and reducing the current dependence on non-renewable resources. Similarly sustainability planning involves, conservation/prevention planning and preparation planning. For a greater sustainable development both planning should be implemented. Sustainability indicators play a crucial role in sustainability planning.

A sustainability indicator is a predefined representation of an attribute affecting the sustainability of the concerned entity. Sustainability indicators are used in various institutional levels. An institution can be a community, a country, a region, an industry or even the whole world. Sustainability is intangible and cannot be measured. But sustainability indicators are tangible and can be measured. In assessment of sustainability the tangibleness of sustainability indicators could be lost in three stages: (1) finding the right indicators, (2) applying the chosen indicators, and (3) scoring the applied indicators. Besides sustainability indicators provide adequate tangibility for making comparison studies between different entities on their sustainability.

2.2. Sustainability assessment in other works

Sustainability indicators has been in existence for long, but it has been brought to effect only after the 1992 Earth Summit held in Rio de Janeiro. From then on a lot of studies have been carried on sustainability and their assessment. Refer to Table 1. Sustainability assessment can be said to have four dimensions namely environmental, social, economical, and institutional. All the four dimensions of sustainability assessment are geographically sensitive, i.e., the sustainability impacts are not equal between countries and regions of the world. Hence assessing sustainability has always been a very complex process.

Most of the studies carried on assessing sustainability take into consideration only three or less than three of the main dimensions of sustainability – environmental, social, and

Table 1 - Some of the existing frameworks on sustainability indicators and their assessment tools. (Hak, Tomas, 2007, s. 12)

No.	Existing frameworks on sustainability indicators	Agency Involved
1.	Commission on Sustainable Development indicator set (UNCSD 2001)	United Nations Commission on Sustainable Development (UNCSD)
2.	Millennium Development Goals (MDGs) indicators	United Nations Department of Economic and Social Affairs
3.	Global Environment Outlook indicators	United Nations Environment Programme (UNEP)
4.	Structural indicators (European Commission)	Eurostat for the European Council
5.	Human Development Index (HDI)	UNDP (United Nations Development Programme)
6.	Life Cycle Analysis – carbon to carbon	N.A.
7.	Material Flow Analysis – based indicators	N.A.
8.	Energy Flow Analysis – based indicators	N.A.
9.	Living Planet Index	World Wildlife Fund
10.	Environmental Sustainability Index (ESI)	Yale and Columbia University
11.	Environmental Vulnerability Index (EVI)	Applied Geoscience and Technology Division of Secretariat Of the Pacific Community (SOPAC)
14.	Driving force– Pressure– State– Impact– Response framework	N.A.
15.	Three-pillar versus four-pillar frameworks	N.A.
16.	Corruption Perception Index, Freedom Index	Transparency International (TI)
17.	Well-being Index	International Union for Conservation of Nature (IUCN)
18.	Environmental Performance Index (EPI)	Yale and Columbia University
19.	Water Footprint	Water Footprint Network
20.	Ecological Footprint	Global Footprint Network
21.	Core Environmental Indicators	Organisation for Economic Cooperation and Development (OECD)
22.	Trade SIA (Sustainability Impact Assessment)	European Commission on Trade

economical. The institutional dimension is usually underrepresented. This behaviour could be explained in a sense that in an institution's point of view on institutional dimension is introverted, which the institutions/companies supporting the studies wouldn't like to express it out loud. Corporations tend to integrate sustainability planning in their corporate strategy, which doesn't necessarily involve all the dimensions of sustainability, so the credibility of those sustainability assessments becomes low.

Many theories and studies have been made for assessing sustainability. The frameworks and tools shown in Table 1 were used in most of those studies. All these frameworks consider only few dimensions of sustainability like environmental and social, the only exception being the sustainability indicators developed by the United Nations Commission on Sustainable Development (UNCSD). UNCSD's Sustainability Indicators considers all the dimensions of sustainability. United Nations is generally believed to be the most neutral international body and covers all institutions; hence facts and figures retrieved from the United Nations can be considered the most viable.

Sustainability assessment has been studied on textiles by both governmental and non-governmental institutions. Some of the popular studies are as followed.

1. EDIPTEX - Environmental Assessment of Textiles: developed by the Environmental Protection Agency of Danish Ministry of the Environment. The study focuses on Life Cycle Assessment of six textile products and their environmental impacts. (Laursen;Hansen;Knudsen;Wenzel;Larsen;& Kristensen, 2007)
2. Environmental impact assessment of man-made cellulose fibres: by the authors belonging to the Faculties of Science and Geosciences in Utrecht University in The Netherlands. (Shen;Worrell;& Patel, Environmental impact assessment of man-made cellulose fibres, 2010) The study was partly funded by Lenzing AG of Austria. A very similar study also appeared in the journal "Lenzinger Berichte". (Shen & Patel, LCA single score analysis of man-made cellulose fibres, 2010, ss. 60-66) The later study was written by two of the three authors of the earlier mentioned study. Both the studies focused on the environmental impact assessment of various man-made cellulosic fibres made by Lenzing in Austria and Asia. The study concluded that it is more sustainable to produce man-made cellulosic fibres in Austria than in Asia.
3. The sustainability of cotton – Consequences for man and environment: by researchers from Wageningen University. (Kooistra & Termorshuizen, 2006) This study explains the sustainability aspects in cotton production and growing.

Though all the above mentioned studies give a good description of the sustainability aspects in textile production, a common and holistic view on sustainability of all fibres is still missing. Polyester though remains the largest consumed fibre, very less importance is given to study the sustainability of polyester and its comparison with that of cotton's and cellulosic's sustainability.

Some of the most commonly used frameworks or standards for sustainability assessment in textiles industry are GRI, ISO 26000, and ISO 14001. ISO 26000 and ISO 14001 are two of the standards of the International Organization for Standardization. ISO 26000 helps assessing the social responsibility of an institution, and ISO 14001 helps assessing the environmental management system of an institution.

Global Reporting Initiative™ (GRI): GRI was formed in the late 90s and partnered with UNEP (United Nations Environment Programme) from 1999 onwards. GRI is a reporting framework centred on sustainability reporting guidelines. Institutions like brands and industries use GRI's Reporting Framework to express their sustainability level against the indicators of sustainable development as given by the GRI's Reporting Framework. GRI's Reporting Framework includes about six types of Performance Indicators. They are as followed.

- Environment
- Economic
- Human rights
- Labour practices and Decent work
- Product responsibility
- Society

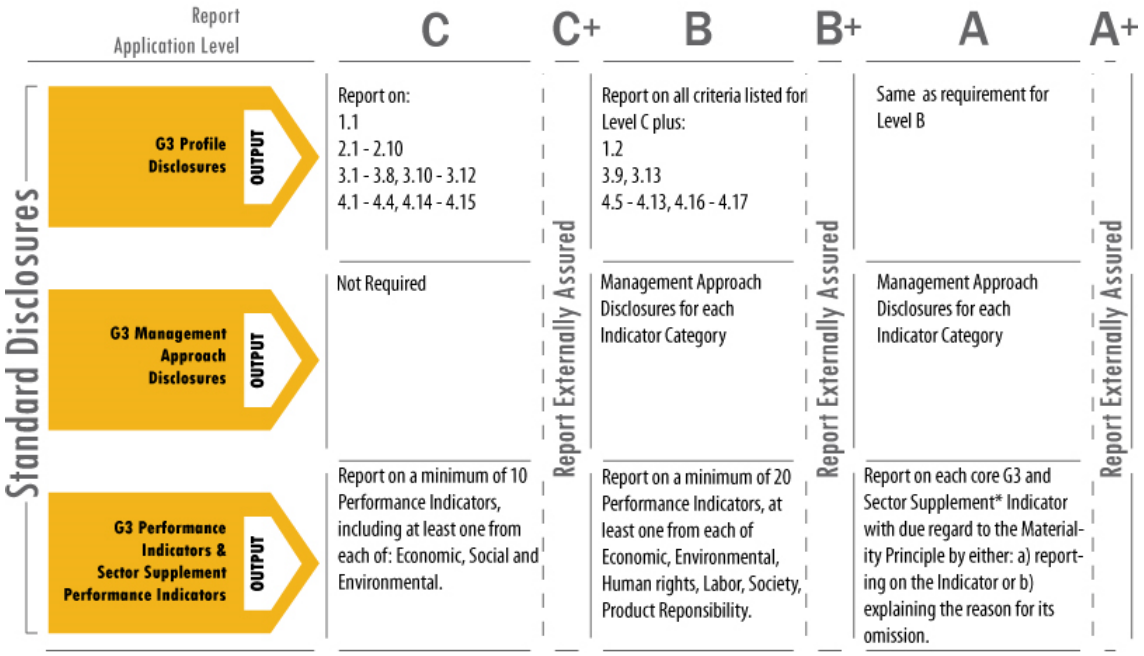

Figure 6 Different application levels in GRI's Reporting Framework. (www.globalreporting.org, 2011)

The main three dimensions of sustainability assessment (environmental, economical, and social) are sub-classified into these six performance indicators. The GRI has its own indicators of sustainable development. The institutions use the reporting framework to report their sustainability in different levels of disclosure across profile, management approach, and performance indicators. The different levels of sustainability reporting in

GRI are classified as levels A, B, and C. '+' sign indicates that the report has been verified and assured externally. (www.globalreporting.org, 2011)

Figure 6 gives a good description of the application levels of GRI, however, the notations appearing in the figure like "Report on: 1.1" and "2.1 – 2.10" is specific to GRI and it is out of the scope of this work. Hence the notations are not explained. Both the frameworks for sustainability assessment are designed only for institutional entities. GRI framework and ISO standards cannot be applied to fibre production systems in general.

2.3. UN's working list of indicators of sustainable development

Sustainability indicators came into effect following the 1992 Earth Summit held in Rio de Janeiro, where the parties in the conference recognized the importance of indicators to help in decision making for concerns on sustainable development. The recognition is articulated in Chapter 40 of Agenda 21, calling countries and various organizations to develop and identify indicators on sustainable development. The UN's 'Commission on Sustainable Development' (CSD) produced the third edition of 'working list of indicators of sustainable development' in 2006.[iv] (United Nations, 2007)

Table 2 - Agencies involved in development of sustainability indicators and acronyms

Acronym	Agency involved in developing the indicators
ILO	International Labour Office of the UN
DESIPA	Department for Economic and Social Information and Policy Analysis of the UN
UNESCO	United Nations Educational, Scientific and Cultural Organisation
FAO	Food and Agriculture Organisation of the UN
HABITAT (or) UNCHS	United Nations Centre for Human Settlement
UNIDO	United Nations Industrial Development Organisation
UNSD	United Nations Statistical Division
UNCTD	Conference on Trade and Development of the UN
UNSO	United Nations Drylands Development (or) Office to Combat Desertification and Drought. Formerly called United Nations Sahelian Office
UNDP	United Nations Development Programme
IUCN	International Union for Conservation of Nature
UNFCCC	United Nations Framework Convention on Climate Change
OECD	Organization for Economic Co-operation and Development
SBC	Secretariat of the Basel Convention
UNEP	United Nations Environment Programme

Commission on Sustainable Development is working along with several agencies of the United Nations in developing these indicators. Every agency leads the development and updating of one or more indicators. The agencies involved in developing indicators and their acronyms are listed in Table 2.

It is believed a significant portion of these sustainability indicators are relevant for a fibre production system, though these indicators have been developed for national level implementation. Considering the fact that there isn't any other globally recognized list of sustainability indicators, applying this list of sustainability indicators makes the most relevance.

The UN's CSD has classified the sustainability indicators into four categories namely social, economic, environmental and institutional. The stakeholders of any industry (including textile industry) would fall under all/any of these classes. The working list of indicators of sustainable development has in total 96 indicators and about 42 indicators have been used in this work. But they are not the core indicators as suggested in the working list, since the core indicators are formed for indicating national level sustainability. I have shortlisted the list of indicators that are relevant to the context of this work i.e., a fibre production system.

The list of sustainability indicators used in this work is shown in Table 3, Table 4, Table 5, and Table 6. Annex 1 shows the full list of sustainability indicators. (UN, 2007)

2.3.1. Environmental sustainability indicators

These indicators express the environmental sustainability. The basic aspects covered by these indicators on an industrial level are consumption and degradation of natural resources like water, land, and forest. They also cover exploitation of atmosphere by emissions, land by waste generation, and ecological diversity by deforestation. Refer to Table 3.

Table 3 - List of environmental sustainability indicators with their sub-classes and agencies involved in development of the indicator.

Indicator classes	Indicators	Agency involved
Protection of the quality and supply of freshwater resources	Annual withdrawals of ground and surface water	FAO
	Ground water reserve	WHO, FAO, HABITAT
	Wastewater treatment	WHO, FAO, HABITAT
Integrated approach to the planning and management of land resources	Land use change	FAO
	Changes in land conditions	FAO

Managing fragile ecosystems: combating desertification and drought	Satellite derived vegetation index	FAO
	Land affected by desertification	UNSO
Promoting sustainable agriculture and rural development	Use of agricultural pesticides	FAO
	Use of fertilizers	FAO
	Irrigation percent of arable land	FAO
	Energy use in agriculture	FAO
	Arable land per capita	FAO
	Area affected by salinization and waterlogging	FAO
	Agricultural education	FAO
Combating deforestation	Wood harvesting intensity	FAO
	Forest area change	FAO
	Managed forest area ratio	FAO
	Protected forest area as a percent of total forest area	FAO
Conservation of biological diversity	Threatened species as a percent of total native species	IUCN
	Protected area as a percent of total area	IUCN
Protection of the atmosphere	Emissions of greenhouse gases	UNFCCC
	Emissions of sulphur oxides	OECD
	Emissions of nitrogen oxides	OECD
	Expenditure on air pollution abatement	OECD
Environmentally sound management of solid wastes and sewage-related issues	Expenditure on waste management	HABITAT
Environmentally sound management of toxic chemicals	Chemically induced acute poisonings	(indicator under development)
Environmentally sound management of hazardous wastes	Area of land contaminated with hazardous wastes	SBC, UNEP

To explain with an example, the indicator "Annual withdrawals of ground and surface water" is developed by FAO (Food and Agriculture Organisation of the UN) and is considered under the indicator subgroup "Protection of the quality and supply of fresh water resources". This explained indicator is one of the twenty seven environmental sustainability indicators. And it carries equal weightage with the entire sustainability indicators.

2.3.2. Social sustainability indicators

These indicators express the facilitation of social welfare. Some of the basic aspects taken into consideration by these indicators are creating jobs, living standards, societal equality, gender equality, working conditions, and child labour. Refer to Table 4.

To explain, the indicator class "Combating poverty" has two indicators in it – (1) Unemployment rate and (2) Head count index of poverty. According to these indicators, in a society like sub-Saharan Africa, the fibre production system of cotton will score better than the fibre production system of a cellulosic fibre. Since cotton production generates more jobs than that of cellulosics, it helps eliminating poverty.

2.3.3. Economic sustainability indicators

These indicators express the sturdiness of an economy on which certain fibre production systems' sustainability gets influenced. Basic aspects taken into consideration are total revenue generated, cost factors, nature of traded goods, factors affecting the production, susceptibility to natural calamities like drought, and GDP contribution of particular fibre production system.

Cellulosics production systems pose harm to the environment when not rightly controlled. Since cellulosics production essentially involves felling of trees for its pulp needs and usage of chemicals in dissolving the pulp and fibre forming/spinning. So the forestry and effluent water has to be controlled effectively to prevent making harm to the environment. The controlling and prevention of the ill effects of a fibre production system in a certain economy is effective only when the economy is strong. The strength of an economy is reflected by the following indicators represented in Table 5.

To explain, when a particular economy has a greater score from the indicator "Environmental protection expenditure as a percent of GDP" (belonging to the class "Financial resources and mechanisms"), it means that it is more sustainable to have cellulosic fibre production systems like that of viscose in those economies. Since the cellulosics fibre production has to be controlled in order to score better in those indicators. That particular indicator will be applied with the information provided by DESIPA (Department for Economic and Social Information and Policy Analysis of the UN) - the agency involved.

2.3.4. Institutional sustainability indicators

These indicators reflect the sustainability of an institution, in this work's context a fibre production system. Refer to Table 6.

Table 4 - List of social sustainability indicators with their sub-classes and agencies involved in development of the indicator.

Indicator classes	Indicator	Agency involved
Combating poverty	Unemployment rate	ILO
	Head count index of poverty	The World Bank
Demographic dynamics and sustainability	Population growth rate	DESIPA
	Population density	DESIPA
Promoting education, public awareness and training	Women per 100 men in the labour force	ILO
Protecting and promoting human health	Access to safe drinking water	WHO
Promoting sustainable human settlement development	Infrastructure expenditure per capita	HABITAT

Table 5 - List of economic sustainability indicators with their sub-classes and agencies involved in development of the indicator.

Indicator classes	Indicator	Agency involved
International cooperation to accelerate sustainable development in countries and related domestic policies	Net investment share in GDP	DESIPA
	Environmentally adjusted net domestic product	UNSD
	Share of manufactured goods in total merchandise exports	UNIDO
Changing consumption patterns	Share of natural resource intensive industries in manufacturing value added	UNIDO
	Share of manufacturing value added in GDP	UNIDO
	Share of consumption of renewable energy resources	DESIPA
Financial resources and mechanisms	Environmental protection expenditure as a percent of GDP	DESIPA

Table 6 - List of institutional sustainability indicators with their sub-classes and agencies involved in development of the indicator.

Indicator classes	Indicator	Agency involved
Integrating environment and development in decision-making	Mandated environmental impact assessment	Division of environmental assessment, UNEP

The indicators Mandated environmental impact assessment explains whether the fibre production systems are monitored on their environmental effects or not. For example, polyester fibre production system is able to be monitored from start to end, and hence can be controlled effectively. Comparing to cotton and cellulosic fibre production system, polyester fibre production system is easier to assess the environmental impact; hence it would tend to score higher.

Like the earth's atmosphere, which is influenced by a lot of factors, a fibre production system also is influenced by a lot of factors. All the factors are mostly independent of each other and affect the sustainability of the fibre production system; hence it is very hard to come up with a quantitative measure for sustainability. I took an approach of grouping all the factors into four groups of sustainability indicators, as explained in this chapter.

It becomes clear that a qualitative assessment of the sustainability is more appropriate than a quantitative assessment, since not all the indicators have equal weight on the sustainability. The qualitative assessment I have applied in this work will be explained in the following chapter.

3. RESEARCH METHODS

3.1. Applying indicators of sustainability to fibre production systems

Sustainability indicators are of varied nature, units, and scope of applicability. It is not possible to create a function involving all the attributes of sustainability (sustainability indicators) and produce an index. There has been certain works published on measuring sustainability, which include a part of the attributes of sustainability under environmental sustainability or social sustainability and produce an index or reference list for comparison and evaluation purposes.[v] [vi] [vii] But overall sustainability analysis of an entity should always be case based. In this work's context the entity is a fibre production system.

This work takes into consideration the fibre production systems of viscose, lyocell, and for referencing purposes cotton and polyester has also been included. As explained before, sustainability indicators have been applied in this case for investigating sustainability of cellulosic fibre production systems. The indicators have to be assessed in order to be compared between the fibre production systems, thus I have introduced a scoring method in this work. The introduced scoring method is completely a qualitative assessment and not quantitative. The scoring method will be explained in the later part of this work. (3.3 Scoring method)

Sustainability indicators of any fibre production system essentially involve all the four dimensions, i.e., environmental, economical, social, and institutional. Most of these indicators, in order to be applied to a fibre production system, must be associated to a country or a region. For example, cotton production in high population density countries like India is not equally sustainable when compared to cotton production in other countries like the USA. As cotton growing affects the food, land and water security of India, which is very crucial for meeting the basic needs of high local population. Also regenerated cellulosic fibre production is not equally sustainable in the tropical and temperate regions of the world. Cellulosic fibre production essentially involves logging for pulp production, which affects the bio-diversity more in the tropical rather than in the temperate regions. So for convenience in applying the sustainability indicators, I have clustered the countries with similar characteristics into country blocks and applied the indicators generally to those blocks representing the countries in them.

3.2. Country blocks

In now globalized world all kinds of fibre production systems can possibly be established almost all over the world. Regenerated cellulosic fibres once evolved in the forest rich parts of the Europe have started to appear also in less forested areas, where the wood pulp is being exported from pulp rich countries. Synthetic fibre producing countries get most of the required raw materials from oil producing countries. This scenario though seems to be less sustainable, as it involves more than one trade within a supply chain, but supports countries with competitive advantages like geographical location and cheap labour. Hence it is almost impossible to associate a fibre production system with countries. And so clustering the countries into country blocks becomes a must.

In this work I have clustered the countries into four country blocks as described in Table 7. The names of all the countries are not mentioned in the below table, but Annex 2 shows all the countries' names (who are members of the United Nations) clustered into these four blocks.

Table 7 - Country blocks as classified in this work and few of their examples. For full list refer Annex 2.

Country blocks	Countries' description
Block 1 - Developed and natural resource rich countries	Well-developed countries and countries with high natural resources per capita. Natural resources like forest and water are considered the most. Like countries of EU-15, Japan, Switzerland, Norway, USA, Canada, Australia, Russia, and New Zealand.
Block 2 - Developing and/or agricultural economies	Countries where agriculture still plays an important role in building the economy, and fast growing countries where environment is of the next priority to national growth and development. Like China, India, Brazil, Mexico, Pakistan, Bangladesh, South Africa, Vietnam, Indonesia,
Block 3 - Economies with competitive advantage(s)	Countries in close proximity with developed countries, and countries with allocated quotas. Block 3 countries have similar characteristics when compared with Block 2 countries. Except in particular cases where the Geographical presence and trade quotas play an important role. All the fibre production systems in Block 3 tend to be more sustainable because of their close proximity to the end markets. Like Central American and East European countries
Block 4 - Less developed economies and others	Countries where a large portion of the population lives in poverty and/or one or all their basic needs are not met. Alleviating poverty is of the most importance. Like Sub-Saharan Africa, other South-East Asian countries, and other South American countries.

Block 1 countries are commonly the developed nations. The common characteristics of Block 1 countries are listed below.

- The exploitation of their natural resources and agriculture are not their main sources of income. Exceptions would be oil producing developed nations like Kuwait, Saudi Arabia, and Norway.
- High natural resources per capita.
- Less agriculture dependence. Cotton fibre and cotton products are usually imported. Exceptions would be the United States and Australia, they produced cotton for the year 2005/2006 about 5.2 million tonnes and 43 thousand tonnes respectively. (Lewin, Menachem; Mark F., Herman, 2007)
- Domestic textiles production industry is relatively small. Textiles production is usually outsourced, and textile goods are imported.
- Relatively high investment in research and development activities. Resulting in enhanced production of new and high technical products.
- Most of the human capital invested is in the forefront (research and development) or in the very end (fashion and brand marketing) of the textile value chain.
- Stringent environmental standards and well monitored exploitation of resources like logging.

Block 2 countries are commonly the fast developing nations. The common characteristics of Block 2 countries are listed below.

- Agriculture plays a major role in the economy of the country. They together form the most part of cotton producing countries.
- Environment is of less priority than economic growth and development.
- Deforestation is in alarming rates. Forests in these countries are cleared for pulp production, agriculture needs and housing needs, since the need is high for the growing population.
- High population density. And less per capita natural resources like water and wood.
- Cheap labour, and therefore most of the clothing production is carried out in these countries. Hence involving mass inflow of fibres and fibre manufacturing raw materials.
- Less expenditure on research and development, when compared with developed countries.
- Lower environmental standards, when compared with developed countries.

Block 3 countries are comprised of countries in close proximity to Block 1 countries like Central American countries, North African countries, and Central and Eastern European countries. Being in close proximity reduces carbon emissions from transportation and lower lead times in supply chain, and so it is comparatively more sustainable to have a fibre production system in a Block 3 country, in the view of trade from a Block 3 country to a Block 1 country. Another group of countries included in Block 3 are those having quotas, either governmental or institutional (textile companies). For example many countries of the South-East Asia like Cambodia, Vietnam, Bangladesh and Sri Lanka, and Central American countries like Honduras, Columbia, Paraguay, and Panama. These countries have quotas for improving their economy and elevating poverty, so having fibre production systems here also gets more socially sustainable comparatively. (Nordås, 2004)

Though countries like China resembles Block 3 countries, in being close proximity to Block 1 countries like Japan and Russia, they still are considered as Block 2 countries. Block 2 and Block 3 countries differ between each other on the edge of population density and amount of natural resources per capita.

Block 4 countries are commonly the less developed countries. The common characteristics of Block 4 countries are to have, all or any of as listed below.

- Less population and less resource exploited for own economical growth.
- A large portion of the population living under poverty.
- Poverty alleviation is of the most importance.
- One or more of basic human needs are not met.
- Poor environmental and living standards.
- Industries are not well established and unemployment rate is high.

3.3. Scoring method

The scoring method used in this work takes into consideration the attributes listed as below.

- About 42 (refer Table 3, Table 4, Table 5, and Table 6) of 96 (refer Annex 1) sustainability indicators given in the UN's working list of indicators of sustainability.
- Four clustered country blocks (Block 1, Block 2, Block 3 and Block 4).
- Four different fibre production systems, namely the production systems of viscose (CV), lyocell (CLY), cotton (CO) and Polyester (PES).

Since only four fibre production systems and clusters of countries are going to be compared, I have used a scale for scores from 1 to 4. Relatively the most sustainable fibre production system for a particular sustainability indicator is given a score 1, the most unsustainable fibre production is given a score 4 for the same sustainability indicator. The same method is also applied for country blocks. In the perspective of a specific sustainability indicator, the most sustainable country block is given a score 1 and the least sustainable is given a score 4.

A sustainability index table is drafted for that particular sustainability indicator, and the scores are multiplied between each fibre production system and country blocks. So the least sustainable fibre production system in a least sustainable country block (for a specific sustainability indicator) will get a score of 16 (4x4), where the most sustainable fibre production system in the most sustainable country block will get a score of 1 (1x1). This scoring system will generate about 16 different scores for 16 different possibilities of having a particular fibre production system in a particular country block. Refer to Table 8.

Table 8 - Sustainability index table of a particular sustainability indicator with all the four fibre production systems and four country block.

Fibre production systems	**Indicator(s)**	**Country block score = 1**	**Country block score = 2**	**Country block score = 3**	**Country block score = 4**
Fibre production system score = 1	i_n	1	2	3	4
Fibre production system score = 2	i_n	2	4	6	8
Fibre production system score = 3	i_n	3	6	9	12
Fibre production system score = 4	i_n	4	8	12	16

Table 9 shows the framework adopted in this work. A table framework is a tabulated form of scores for a particular fibre production system, as denoted in the upper cell of the table.

Table 9 - Scoring framework for measuring relative sustainability indicator for a fibre production system

Fibre production system: CV or CLY or CO or PES					
Indicators of sustainability, *i*	i_n	**Sustainability scores**			
		Block 1	**Block 2**	**Block 3**	**Block 4**
Annual withdrawals of ground and surface water	i_1				
Ground water reserve	i_2				
Wastewater treatment	i_3				
Land use change	i_4				
Changes in land conditions	i_5				
Satellite derived vegetation index	i_6				
Land affected by desertification	i_7				
Use of agricultural pesticides	i_8				
Use of fertilizers	i_9				
Irrigation percent of arable land	i_{10}				

Energy use in agriculture	i_{11}				
Arable land per capita	i_{12}				
Area affected by salinization and water logging	i_{13}				
Agricultural education	i_{14}				
Wood harvesting intensity	i_{15}				
Forest area change	i_{16}				
Managed forest area ratio	i_{17}				
Protected forest area as a percent of total forest area	i_{18}				
Threatened species as a percent of total native species	i_{19}				
Protected area as a percent of total area	i_{20}				
Emissions of greenhouse gases	i_{21}				
Emissions of sulphur oxides	i_{22}				
Emissions of nitrogen oxides	i_{23}				
Expenditure on air pollution abatement	i_{24}				
Expenditure on waste management	i_{25}				
Chemically induced acute poisonings	i_{26}				
Area of land contaminated with hazardous wastes	i_{27}				
Unemployment rate	i_{28}				
Head count index of poverty	i_{29}				
Population growth rate	i_{30}				
Population density	i_{31}				
Women per 100 men in the labour force	i_{32}				
Access to safe drinking water	i_{33}				
Infrastructure expenditure per capita	i_{34}				
Net investment share in GDP	i_{35}				
Environmentally adjusted net domestic product	i_{36}				
Share of manufactured goods in total merchandise exports	i_{37}				
Share of natural resource intensive industries in manufacturing value added	i_{38}				
Share of manufacturing value added in GDP	i_{39}				
Share of consumption of renewable energy resources	i_{40}				
Environmental protection expenditure as a percent of GDP	i_{41}				
Mandated environmental impact assessment	i_{42}				
Sum of scores, ($\sum_{i=1}^{n} S_i$)					
Relative sustainability indicators of a fibre production system					

Table 9 is divided into two basic columns, one representing the indicators of sustainability (*i and* i_n), and the other represents the sustainability scores according to respective blocks and whole (S_{in}). The lower cells are the summation of S_{in} and the average of it (i_{rs}), which is the relative sustainability index. The averages of all the sustainability indicators for the four fibre production systems will be tabulated in the Relative sustainability index.

3.4. Assumptions

This scoring method has adopted certain assumptions as listed below.

- The other indicators of sustainability, apart from the 42 considered here, won't affect significantly the sustainability of any fibre production included in this work.
- All the indicators of sustainability (*i*) mentioned in this work carry equal weight with each other, at least qualitatively.
- Overlapping of the country characteristics between the country clusters or blocks is neglected.
- There are no significant differences in fibre production systems between two different countries or blocks.
- The changes in the country characteristics and fibre production systems' attributes are negligible for the time this work is scoped for.
- Block 1 countries remain the biggest consumers of traded textile goods. Carbon footprint in logistics considered in this work will be proportional to proximity of the country where textile goods are exported from, i.e., farer the distance higher the carbon footprint. Hence traded textiles from Block 3 countries carry less carbon footprint and are more sustainable than any other Block country.

3.5. Relative Sustainability Index

Accounting to various factors, like limited access to data from production systems around the world and relevance of process attributes in different fibre production systems, it is hard to come up with a quantitative index to compare the sustainability of different fibre production systems. Hence relative sustainability indicators and a relative sustainability index has been introduced in this work.

A relative sustainability indicator is an average score given to a fibre production system in a particular country block for its various sustainability indicators. This means, 16 different combinations of four fibre production systems and four country blocks involved in this work will generate 16 relative sustainability indicators. Each relative sustainability indicator is an average score of 42 sustainability indicators given to a combination of a fibre production system and a country block.

The relative sustainability indicators are quantitatively manipulated, with the mathematical expression as shown as followed.

$$I_{rs} = \frac{\sum_{i=1}^{n} S_i}{n}$$

$I_{rs} = relative\ sustainability\ indicator$
$r =\ a\ particular\ fibre\ production\ system$
$s = a\ country\ block$
$S_i = A\ \text{fi}bre\ production\ system'score\ for\ a\ specific\ indicators\ (i)$
$i = a\ specific\ indicator\ of\ sustainability$
$n = number\ of\ indicators\ \text{of}\ sustainability\ applied$

To explain the expression, the relative sustainability indicator (I_{rs}) of a fibre production system is an average of all the given scores for indicators of sustainability (S_i) applied for that particular fibre production system. Each fibre production system will have a set of scores given qualitatively on each sustainability indicators (i). The average of all the scores – summation of the scores divided by the number of sustainability indicators applied for that particular fibre production system (n), will give the relative sustainability indicator (I_{rs}) for the fibre production system. Similarly, each fibre production system will carry a relative sustainability indicator ranging from 1.0 to 16.0.

An index comprising of all the fibre production systems' relative sustainability indicators is called as relative sustainability index. Though the relative sustainability indicators are quantitative, the relative sustainability index is purely a qualitative index, which ranks different fibre production systems in different country blocks specifically to a single ranked index. Since the relative sustainability index being qualitative, the values of the relative sustainability indicators (applied of different fibre production systems in different country blocks) will be rounded to the next whole number from 1 to 16 irrespective of the differences between successive values.

So according to this work, the fibre production system in a specific country block with value 1 in the relative sustainability index is the most sustainable fibre production system, and the fibre production system in a specific country block with value 16 in the relative sustainability index is the least sustainable fibre production system.

The index and indicators introduced in this work are to express my view qualitatively on different fibre production systems. The introduced indicator (I_{rs}), index, and score - S_i, must not be understood or used as a quantitative assessment of any particular fibre production system.

4. CELLULOSIC FIBRE PRODUCTION SYSTEMS

Textile fibres have long been researched to cover a wide range of properties to support its three basic needs - thermo physiological comfort, environmental protection, and aesthetic enhancement. Though there are certain fibres like polyester and cotton which have been engineered to cover the most needs, but fibres like other regenerated cellulosics have not lessened their significance or their applications. Cellulosic fibres until now serve more the niche/functional needs of a textile, covering a wide range of properties. But in order to serve a major portion of the market demand, cellulosics will have to be socially and commercially engineered.

4.1. Cellulosics

Cellulose is the most abundant naturally occurring polymer; it constitutes about 40% of the wood matter naturally grown in trees and plants. Figure 7 shows the chemical structure of a cellulose polymer. All cellulosic substances have the same polymeric structure, but they differ in degree of polymerization and the total percentage of cellulose present in the substance. The differences are attributed between different species of the cellulose growing plant/tree and their growing conditions.

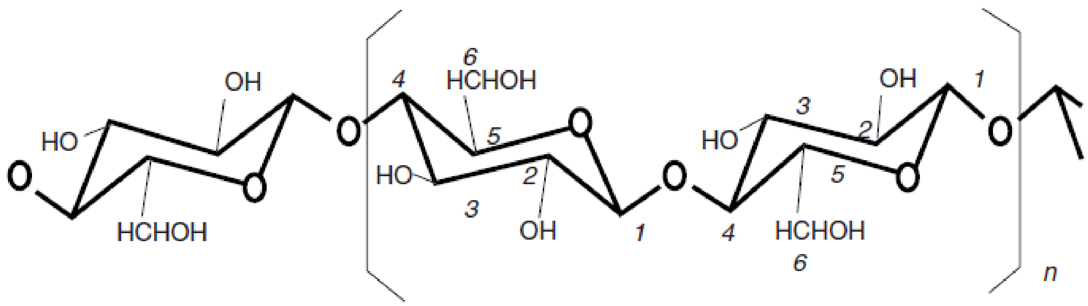

Figure 7 Polymeric cellulose structure with two anhydroglucose units with a 1–4 b-glucosidic linkage. (Woodings, Regenerated cellulose fibres, 2001, p. 2)

Cellulose is the building constituent of plant matter. The atmospheric carbon is absorbed through photosynthesis by the plant cells, stored and used as building blocks for the plant growth. Literally the immediate early degree of carbon present in the cellulosic fibre is atmospheric carbon.

Cellulose fibres are those made of cellulose polymers. Cotton – the most popular cellulose fibre contains about 88% to 96% of cellulose in its dry weight. (Lewin, Menachem; Mark F., Herman, 2007) Any fibre made of cellulose can be called cellulose fibre or cellulosic fibre. Most commonly cellulosic fibres are usually referred to manufactured cellulosic fibres. Cellulosic fibres can be classified majorly into natural and manufactured. The manufactured cellulosic fibres are further classified into regenerated and derived cellulosic fibres. Table 10 shows the general classification of cellulosic fibres with some examples on fibres belonging to their category.

Cotton and linen are the most used natural cellulose for clothing. Bast fibres are mostly used in packaging and other industrial applications. Derived cellulose fibres like acetate fibres are used in filter tows (cigarette tows) and triacetate fibres are used in silk imitating fibres accounting to their silk like feel. Regenerated cellulosics have a versatile scope of applications, like they can be process modified to suit industrial applications and also to suit intimate use.

Regenerated cellulosic fibres can further be classified based on their production process like viscose and lyocell processes. Conventional regenerated cellulosic fibres like viscose and modal are produced by viscose process, and lyocell fibres are produced by lyocell process. Lyocell process is gaining popularity since its introduction owing to its high solvent recovery ability, recovering almost all of the NMMO used. The regenerated cellulose fibres find a varied application, and have the most scope for mass consumption. As of the year 2001 the installed production capacities of different cellulosic fibre production systems are viscose = 2845 k tonnes/annum, lyocell = 100 k tonnes/annum, and acetate = 935 k tonnes/annum.

Table 10 - Classification of cellulosic fibres. (Röder;Moosbauer;Kliba;Schlader;Zuckerstätter;& Sixta, 2009)

Cellulosic fibres	
Natural cellulosic fibres	Manufactured cellulosic fibres

• Cotton, CO
• Linen
• Flax
• Jute
	• Regenerated cellulosic fibres
	  • Viscose, CV
	  • Modal, CMD
	  • Lyocell, CLY
	  • Cupro, CUP
	• Derived cellulosic fibres
	  • Acetate, AC
	  • Triacetate, CTA

This work focuses more on the regenerated cellulosic fibres. Hence the two fibre production systems, viscose and lyocell, are discussed in detail in this chapter.

Excluding cotton, wood is the basic raw material for most of the cellulosic fibre production systems. For certain cellulosic fibre production systems like linen, jute, flax, and hemp, wood is not the source of cellulose, rather it is bast (cell wall of grasses and other di-cotyledons) and other seed fibres. The production and applications of these non-wood cellulosic fibres are very limited and not viable for mass production, since the raw materials availability is low and the production is complicated with longer processes. Regenerated cellulosic fibres are those fibres made from dissolution of wood (in rare cases also other plant cellulose), and regenerated into fibres. Regenerated cellulosic fibres production systems basically involve the following processes.

- Wood harvesting
- Pulp preparation
- Cellulose dissolution
- Fibre forming / spinning
- Cellulose functionalisation / post-spinning process

Naturally present cellulose is cultivated and made into pulp. The pulp is dissolved and later spun into fibres. Functionalisation of cellulosic polymers is possibly done in-between any of the processes mentioned above. Functionalisation is the process of addition of properties artificially to the polymer.

Since the invention of cellulosic fibres, a lot of different processes and fibres have been invented. Fibres of extreme properties have been developed without changing much the process or raw materials. For example viscose (CV), tyre cord, Modal (CMD), and polynosic fibres are all produced by similar viscose process, but their production processes differ only in spinning and after treatment, which is called functionalisation. (Röder, Moosbauer, Kliba, Schlader, Zuckerstätter, & Sixta, 2009) Hence it is understood that in the manufacturing of cellulosic fibres, each process involved have great influence on the properties of produced fibres.

This chapter will explain by each step in to the production systems of cellulosic fibres with a sustainability view.

4.2. Wood harvesting

Wood is the basic raw material source for most of the cellulosic fibres. In very few cases cotton linters are used as raw materials. Cotton linters have a higher percentage of alpha cellulose content (88% to 96%) when compared to that of wood (40% to 50%) (Lewin, Menachem; Mark F., Herman, 2007). Fibres spun from cotton cellulose like Cuproammonium rayon, have better properties but are less viable for mass production due to limited availability of cheap cotton cellulose.

Wood for cellulose production is generally harvested all around the world and is wholly classified into two different types of wood cellulose, hardwood cellulose and softwood cellulose, produced from their respective hard/soft wood species. The lyocell process currently uses mainly hardwood grown in tropical regions, (Andrea, 2011) but it is capable of using any types of wood. (Sixta H. , 2011) Viscose process uses pure and mixtures of both hardwood and softwood grown all over the world.

The softwood species are generally found in the forests of the northern hemisphere. Species like larch (*Larix sibirica*) of eastern Siberia, Scots pine (*Pinus silvestris*) and Norway spruce (*Picea abies*) are softwood species grown in the northern Europe and Asia. Species like white and black spruce (*Picea glauca* and *P. mariana*), balsam fir (*Abies balsamea*), and jack and lodgepole pine (*Pinus banksiana* and *P. contorta*) are grown in North America. (Lönnberg, 2001)

Hardwood species are generally found below the latitudes of softwood forests, and a few important species are birch (*Betula* sp.), aspen (*Populus tremula* and *P. tremuloides*), oak (*Quercus* sp.), gum (*Nyssa* sp.), maple (*Acer* sp.) and beech (*Fagus* sp.). (Lönnberg, 2001) Refer to Figure 8.

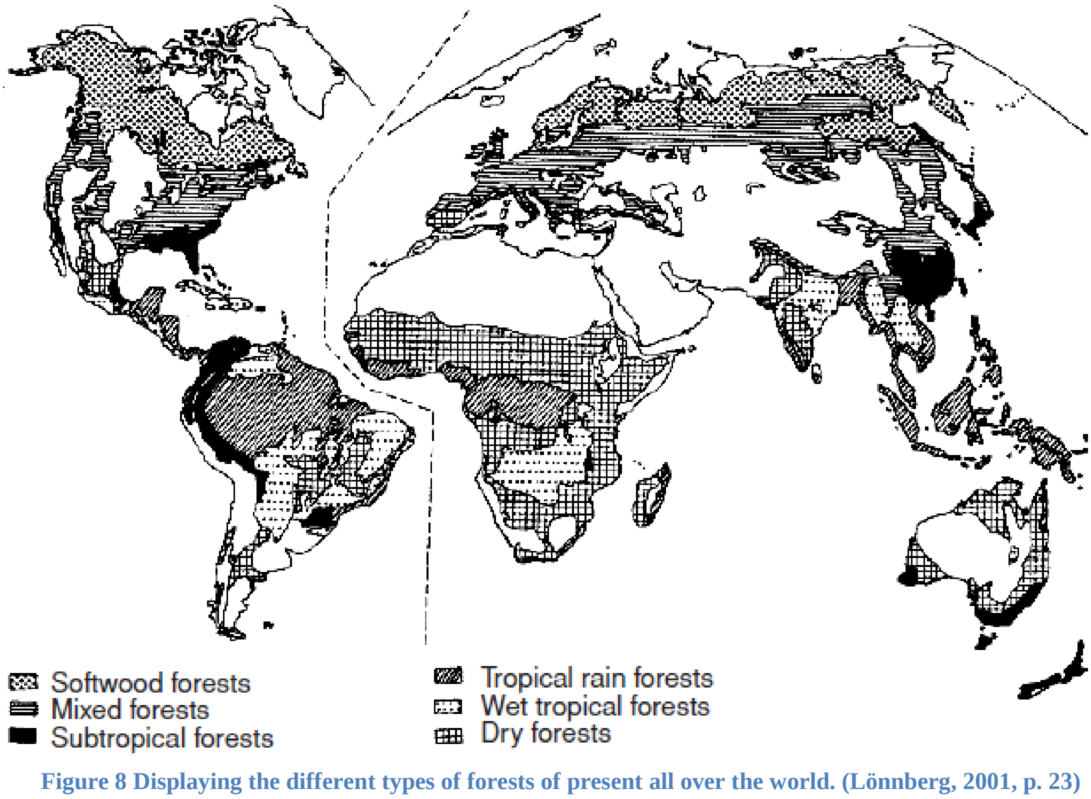

Figure 8 Displaying the different types of forests of present all over the world. (Lönnberg, 2001, p. 23)

A large portion of the world’s forest is found in the northern hemisphere, since most of the land on earth is spread over the northern hemisphere. The temperate climatic conditions prevailing northern Europe, Russia, North America, and Japan (Block 1 countries) is home for the most of softwood forests in the world. The rest of the world’s forests are mixed and tropical forests, except the arid forests. The mixed forests and tropical forests are home for most of the flora and fauna, i.e. they have the habitats for most of the living species of plants and animals.

On a general consideration Block 1 countries are home to most of the temperate forests present in the world, and Block 2, 3, and 4 countries are home to most of the tropical forests in the world. Since the Block 1 (very northern countries) has harsher climatic conditions, they are less densely populated and hence they have high natural resources (like forest) per capita. Other developed countries, which have fewer natural resources per capita but are highly developed, still don't fall in Block 1 but rather they fall in Block 2 countries.

The advantages of wood harvesting in Block 1 countries over Block 2, 3, and 4 countries are,

- Bio-diversity is less disturbed in temperate forests (Block 1) rather than in tropical (Block 2, 3, and 4) forests, and
- Tropical forests provide more non-wood products including food, which helps the communities living in the proximity of forests.

And the only disadvantage is,

- The total land area required for growing a unit amount of wood in a unit amount of time is higher for temperate forests than tropical forests, since the rate of growth of temperate trees is slower by more than half of the rate of growth of tropical trees.

Lenzing AG is the only company manufacturing cellulosic fibres from lyocell process, under its trademark Tencel®. According to the information obtained from Lenzing AG, Tencel fibre making consumes pulp mainly from tropical woods (Eucalyptus sp.) in the southern hemisphere. (Andrea, 2011) Though it is possible to produce lyocell fibres from temperate wood pulps, Lenzing prefers to use tropical wood pulps for various reasons. Some of the reasons as learned from Lenzing's sustainability report and annual reports are as follows, (Lenzing, 2008)

- Tencel fibre yield per area is up to four times higher than cotton (USA and China)
- Water consumption is up to 20 times lower than cotton (USA and China)
- Required acreage for producing a unit amount of Tencel is almost three times lowers than viscose from temperate pulps and just less than four times than cotton (USA and China) (Shen & Patel, 2010, p. 267)

Wood pulps from the Eucalyptus species of the Amazon are generally thought to be used for producing Tencel® fibres.

So this work will consider lyocell (CLY) as a process using only tropical wood pulps and viscose (CV) as a process using both tropical and temperate wood pulps.

4.3. Pulp preparation

Pulp is a form of cellulose made by processing cellulosic raw materials like wood, bagasse, straw, fibres/linters, and paper/board to be recycled. The wood harvested from the forests is transported mostly in the form of wooden logs, or in any smaller forms depending on wood source used for making pulp. The logs are debarked, cut in to chips, and fed in to the processing stages of pulp preparation. The pulp made from bagasse and straw uses agricultural by-products like sugarcane bagasse from sugar mills and straw from other cultivated crops, which is transported as bales or just in the fluffy form directly from the mills. China is the largest producer of straw pulps amounting to 12 million tons a year, comparing to the wood pulp production capacity of Finland being at 14 million tons in a year. (Lönnberg, 2001) Fibres/linters are the by-products of the ginning and spinning mills, where the seed cotton wastes from ginning and short fibre wastes from spinning are used. Recycled paper and board use used paper and board as source for pulp making.

Various classifications of pulps

Pulps can be classified under many classifications like based on

i. Nature of wood used:
   - Hardwood pulp
   - Softwood pulp
ii. Pulp dissolution:
   - Dissolving grade
   - Paper grade pulp
iii. Traded pulps:
   - Market pulps
   - Fluffy pulps
iv. Pulping methods:
   - Mechanical pulping
   - Thermo-mechanical pulping
   - Chemo-thermo-mechanical pulping
   - Chemical pulping (Kraft process)

In cellulosic fibre production both hardwood and softwood pulps are used. Only the dissolving grade pulps can be used for cellulosic fibre production, since the pulp has to be dissolved for fibre spinning. Paper grade pulp is produced by removing most lignin and resins from the digested stock. Dissolving grade pulp is produced by removing hemicelluloses from the paper grade pulps. Hence dissolving grade pulps are the purest form of cellulose, containing about 90% to 94% of alpha cellulose, available as pulp. (Shen, Worrell, & Patel, 2010) Both dissolving and paper grade pulps have to be bleached depending on the application of the pulps. Bleaching of the pulps removes all lignin and impurities present in the pulp and hence it dissolves completely in cellulose solvents.

The traded pulps classification is only used when the pulp is traded. Fluffy pulp is the loose form of pulp after pulping, whereas market pulp is the compressed form of fluffy pulp. Market pulp is manufactured and prepared for transportation. Market pulp requires two additional steps in processing of the pulp, like compressing the fluffy pulp before transportation and opening of the pulp fluffs after transportation.

The pulping process

The processing of cellulosic raw materials to make pulp is called pulping. Pulping is done predominantly by two methods: mechanical pulping and chemical pulping. Mechanical pulping is the oldest method of pulping, but it is used now only in paper and board industry. Chemical pulping is the most used pulping method in the pulp industry, and it can be used for any applications of pulp like fibre and paper production. The most used chemical pulping method is the Kraft pulping process. The Kraft pulping process is an alkaline process, which uses sodium hydroxide and sodium sulphide as active delignification chemicals. (Lönnberg, 2001)

Pulping preparation is the same for both mechanical and chemical pulping methods. After the wood logs are debarked, cut into chips, and screened, they are fed into the pulp digester. In mechanical pulping the digestion is done by severe beating of the wood chips to break them into smaller pieces and then to digested pulp. In chemical pulping the wood chips are cooked in a chemical solution of sodium hydroxide and sodium sulphite. The digested stock is then washed to remove the chemicals and dissolved organic substances. The residue stock (pulp) is basically having higher fibre content from the wood with fewer impurities. The pulp thus produced is brown in colour, the natural colour of lignin, and depending on the application the pulp can be either bleached or not. For paper making the pulp has to be bleached, but for other applications like making boards and cartons it doesn’t necessarily have to be bleached.

Various other different forms of pulping processes are still in use but not as extensively as the above mentioned mechanical and chemical pulping processes. Different forms of pulping processes, and their comparative classification is explained below.

4.3.1. Chemical pulping

Chemical pulping is the most common form of pulping and also the most efficient. Comparing it with other pulp extractions forms, like mechanical pulping, chemical pulping consumes a lot less energy and removes lignin and hemi-celluloses effectively from the wood matter. Almost all dissolving pulps are chemical pulps. The only disadvantage and also currently the biggest concern in pulp industry is the usage of chemicals during pulp extraction. All chemical pulping methods use particular chemicals to dissolve/disintegrate the resins, lignin, and hemicelluloses from the wood matter. Though modern methods have developed to almost complete chemical recovery systems, still some portion of the used chemicals/refuse is let in the environment, which deposits sulphur and other toxic chemicals into the ground and water.

Chemical pulping can be broadly differentiated into three types of pulping process like sulphate process with pre-hydrolysis (Kraft process), sulphite process (main pulping method for producing dissolving grade pulp), and soda process (not used anymore). The main difference between these processes is only the nature of chemicals used.

4.3.1.1. Pre-hydrolysis Kraft pulping:

Kraft pulping is the most used pulp extraction method in the whole world, accounting to 90% of all the chemical pulps. (Sixta & Schild, 2009) It was first developed by Carl F. Dahl in 1879 followed by the founding of first Kraft pulping mill in Sweden in 1890. Kraft process pulps use wider variety of both hard and soft wood. The fibres from Kraft pulping process have less tensile and tear strength when compared to mechanical pulping process, as most of the lignin present in the wood matter is removed. But still Kraft produces the strongest fibres of all the chemical pulping methods.

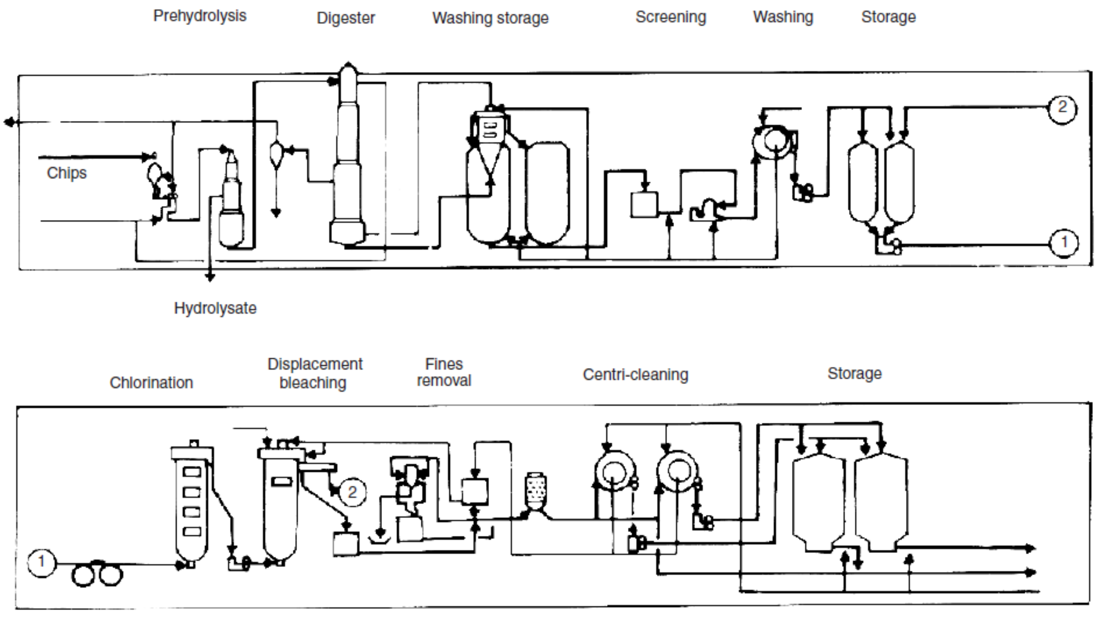

Figure 9 Prehydrolysis Kraft pulping followed by modern displacement bleaching. (Lönnberg, 2001, p. 29)

Kraft pulping process is basically an alkaline pulping process which uses sodium hydroxide and sodium sulphide as active delignification chemicals. (Lönnberg, 2001, p. 23) Chemical recovery with recovery boiler in a Kraft has the potential to recover almost all of the pulping chemicals, which is reused in further pulping process. Refer to Figure 9.

4.3.1.2. Sulphite process

Sulphite process is another chemical pulping process which is based on sulphur dioxide with varying cation, pH and cooking temperature. Acidic calcium bi-sulphite $Ca(HSO_3)_2$ is generally the dissolving chemical used in Sulphite process. The process is more acidic than Kraft process and hence degrades the fibres more resulting in less strong fibres. The chemical recovery produces insoluble calcium sulphate making the chemical recovery potential much lower than Kraft process. This pulping process is less sustainable and polluting. Another reason is that the use of this pulping process is limited to only spruce wood.

Developments in this pulping method resulted in the use of soluble cations like magnesium, sodium and ammonia. These developments also increased the pH (less acidity) from 1-2 up to 5 for magnesium bi-sulphite process. (Lönnberg, 2001, p. 23)

4.3.1.3. New pulping methods

A lot of recent developments have been made in the pulping process to find different ways of pulping which are eco-friendly (less chemical usage) and energy efficient. Some of the concepts of these new pulping processes are still under development or pending patent approvals. Some examples are enzymatic pulping and chemo-enzymatic pulping by using enzymes and fungi.

Herbert Sixta and Gabriele Schild came up with a new pulping process in their paper – "A new generation Kraft process" in Lenzinger Berichte 87 (2009). The process is carried by applying pre-hydrolysis and pre-alkaline extraction to *Eucalyptus globulus* followed by Kraft and Soda-AQ pulping. They claimed to have achieved higher pulp yield while extracting xylan (a constituent of hemicelluloses in wood) in polymeric form in the pre-step. Also the produced pulp can be used as paper grade and dissolving pulps without bleaching. (Sixta & Schild, 2009, pp. 26-37)

Recovery and reuse of pulp refuses

Pulping process dissolves or removes more than half of the total composition of wood by weight. The dissolved refuses from the pulping process contain the dissolved organic compounds and chemicals used for digestion. Recovering the chemicals from the refuse reduces the environmental effects and also supplies chemicals to the next pulping process, which also saves a lot of money on chemicals. The dissolved organic compounds from the refuse are used as a fuel source for energy production and as raw materials for producing some industrial chemicals. Modern pulp mills produce more energy than they consume which they sell as one of their by-products.

Recovery and reuse of the chemicals and refuses is the most important part of the pulping process and also for cellulosic fibre production systems in the view of sustainability, since they reduce the environmental impacts of pulp preparation which is the main polluting part of the cellulosic fibre production systems. Kraft pulping process has the highest chemical recovery potential, above 99%, than any other pulping process.

Generally a pulping process yields around 35% to 53% of pulp from the fed wood matter. Pre-hydrolysis Kraft processed pulp, which is one of the finest dissolvable grade pulps, contains about 98% cellulose but the pulp yield is only 35%. Such high cellulose content pulps are needed for acetate fibre productions. Hence it is understood that the purity of pulp (cellulose content in the pulp) is indirectly proportional to the pulp yield. (Lönnberg, 2001, p. 33)

4.4. Cellulose Dissolution

Cellulose does not melt or dissolve due to presence of very strong intermolecular bonds between the polymeric chains. In order to be able to spin cellulose into fibres they have to be dissolved at some form, extruded, and spun. Hence cellulosic fibre production systems involve cellulose dissolution in various solvents. Dissolving grade pulp contains more than 90% cellulose in it and it is the only form of pulp suitable for cellulosic fibre production. In the year 1998 the total world pulp production was 175.5 million tonnes and the chemical pulps alone constituted about 123.6 million tonnes. The dissolving grade pulps constituted about 3.51 million tonnes (2%) in total world pulp production and 3.46 (2.8%) million tonnes of all the chemical pulps; which means about 50,000 tonnes of dissolving grade pulps are produced from non-chemical pulping methods. (Lönnberg, 2001, p. 31)

Cellulose can be dissolved in various solvents. The solvents used for dissolution is a main attribute for a cellulosic fibre production system. The processes in pre-extrusion and post-extrusion of cellulosic polymers during fibre forming, should suit the cellulose solvent used. So it can be said that cellulose solvents are the process makers. Refer to Table 11.

Cellulose solvents differentiate the characteristics of the dissolved cellulose, and so it also changes the properties of the cellulose polymers after spinning. For example, lyocell is basically a viscose process, but the cellulose solvent used is NMMO whereas in viscose it is alkali and carbon disulphide. NMMO doesn't form any intermediate chemical form of the dissolved cellulose, and hence the process chain has been reduced. On the other hand, viscose, modal, and polynosic are produced from the same viscose process and solvents but differ in the spinning process and after treatment. They form a wide range of properties together.(Röder, Moosbauer, Kliba, Schlader, Zuckerstätter, & Sixta, 2009) The solvent actions of viscose and lyocell processes will be explained in the next chapter.

Table 11 - Most used fibre production systems with their process names, cellulose solvents, and process intermediaries. (Woodings, 2001) (Kotek, 2007)

Fibre production system	Process	Cellulose solvents	Intermediate / derivatives formed
Viscose	Viscose	Alkali and carbon disulphide	Cellulose Xanthate
Lyocell	NMMO (or) Amine oxide (or) Lyocell	*N*-Methylmorpholine-*N*-oxide	No intermediaries formed
Acetate	Acetate	Acetic anhydride	Cellulose (Tri)acetate
Cuprammonium	Cupro	Copper oxide + aq. Ammonia	Cellulose cuprammonium complex
Cellulose Carbamate	Carbamate	isocyanic acid from urea	Cellulose carbamate
Akzo fibres	Akzo phosphoric acid process	Anhydrous phosphoric acid	

The cellulose acetate process uses acetic anhydride as solvent. Acetic anhydride is produced by cracking reaction of acetic acid and acetone. Cellulose in the pulp forms cellulose acetate which when spun gives cellulose acetate fibres or cellulose di-acetate or cellulose tri-acetate fibres. Acetate fibres find their most use as cigarette tow. (Woodings & Hearle, 2001)

Cuprammonium ions ($Cu(NH_3)_4^{+2}$) forms a complex with the hydroxyl groups of cellulose, which makes it able to dissolve. The thus solved solution when spun forms cuproammonium fibres. These fibres are washed with 5% H_2SO_4 to remove the copper present in the fibres to copper sulphate. Copper sulphate is highly toxic, which is the biggest disadvantage in this process. Cupro fibres produce silky fibres and they are also called as artificial silk. They are highly flammable thus limiting the applications. But still these fibres find uses such as dialysis membranes, known as Cuprophane. (Kotek, 2007)

Isocyanic acid made from urea dissolves cellulose to form cellulose carbamate. Urea is just a cheap raw material for Isocyanic acid, but Isocyanic acid can be made from other sources too. Another process for synthesizing cellulose carbamate was achieved by researchers from Neste Oy. They used activated cellulose, activated by treating cellulose with liquid ammonia at -35°C, and treated the activated cellulose with urea at 135°C to 145°C to form cellulose carbamate. This process carries high cost, but is more eco-friendlier than viscose. The fibres spun from this solution have a similar property profile with that of viscose (Kotek, 2007)

The phenomenon of the Akzo process is dissolving cellulose in another cellulose solvent called anhydrous phosphoric acid, and regenerating the fibres. After dissolving the cellulose in phosphoric acid solution it is extruded through spinnerets and the fibres are wet spun. The fibres are washed in water to remove phosphoric acid and finally with 2% sodium carbonate. A similar fibre forming process dissolving cellulose in anhydrous sulphuric acid produces Kevlar fibres. Both Kevlar and Akzo process produce stronger and high performance fibres. Akzo process reduces the DP (degree of polymerization) of cellulose polymers. For example cellulose polymers of average DP around 800 if used in Akzo process produces fibres with cellulose polymers of average DP around 620.

Some other cellulose solvents which have due importance to be mentioned here are,

- *N*,*N*-Dimethylacetamide (DMA) and Lithium Chloride (LiCl)
- Trifluoroacetic acid
- Nitrogen dioxide (N_2O_4)
- Unconventional solvents like
    - Ionic Liquids (ILs)

Many of these solvents are not used commonly for the reasons they form less stable intermediaries like nitrogen dioxide forming cellulose nitrate. Certain other solvents pose a larger environmental threat. And solvents like ILs (Ionic Liquids) and steam with Alkali are still under research and development. (Kotek, 2007)

Ionic Liquids are salts of lower melting points (< 100°C). ILs are the only cellulose solvents which has higher potential than NMMO in lyocell process for chemical recovery in cellulose dissolution. A good Ionic Liquid should not cause decomposition of cellulose, should be storable, stable, eco-friendly, cheap and have good recovery potential. At room temperatures these solvents have a large proportion of ions ready to react. 1-butyl- and 1-allyl-3-methylimidazolium chlorides and 1-ethyl-3-methylimidazolium acetate are good solvents for cellulose. Refer to Figure 10.

Certain cellulose solvents substitute the use of pulping chemicals, like they extract the cellulose from the wood matter by dissolving cellulose already in the first place. In this way also a large proportion of hemicelluloses and other impurities are also carried, and so it is not recommendable. The major difference between cellulose solvents and pulping chemicals are that cellulose solvents dissolve the cellulose fibres in the wood matter, whereas the pulping chemicals dissolve the non-fibre cellulose constituents of the wood matter like resins, lignin, and hemicelluloses and leave the fibrous cellulose in pure form.

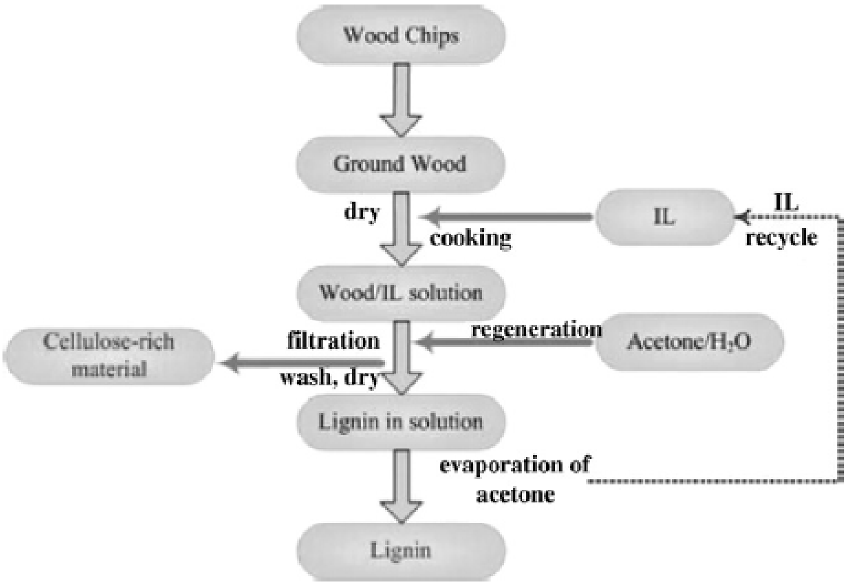

Figure 10 Process flow showing dissolution of wood by Ionic Liquids. (Mäki-Arvela, Anugwoma, Virtanena, Sjöholma, & Mikkola, 2010, p. 199)

4.5. Fibre formation

Dissolved cellulose solution is usually passed into fluids (liquid or air solutions) removing the cellulose solvents from the just extruded fibres to spun fibres. The nature of processes involved, chemicals used, and recovery of those chemicals from thus removed solvents differentiates majorly the cellulosic fibre forming processes. The two major fibre forming processes, viscose and lyocell, are dealt in this section.

4.5.1. Viscose process

Viscose fibre is formed by initially treating the pulp in caustic soda, which makes the cellulose in the pulp to depolymerise. The depolymerised cellulose is then treated with carbon disulphide to form cellulose xanthate. Cellulose xanthate is the intermediate formed in viscose process. Cellulose xanthate is later dissolved in aqueous alkali solution to form the spinning solution. The mixture is left to age and ripen to form a yellow viscous solution of cellulose. The name viscose comes from "the viscous solution of cellulose", which later became the name of the fibre and it's making process.

The spinning solution of viscose fibres contains about 7-10% of cellulose, 5-7% of sodium hydroxide, 25-35% of carbon disulphide, and the rest water. Modal fibres are one of the variants of viscose fibres formed from the same cellulose solvent and same viscose process. The process parameters for modal are set so that the spinning solution contains 6-8% cellulose, 6.5-8.5% sodium hydroxide, 30-40% carbon disulphide, and the rest water. Both the fibres are wet spun in a spinning bath of sodium sulphate. Viscose spinning solution in addition will have sulphuric acid and zinc sulphate.

Steeping is the first process in the production of viscose fibres where pulp is soaked in aqueous sodium hydroxide to make the cellulose in the pulp to swell. The pulp is left to steep until it swells around 2.8 times its own weight. At this stage the alkali-cellulose proportion will be around 15-35% respectively with the rest being water. To transport the steeped pulp (alkali-cellulose) is compressed to remove the excess water in it and shredding should be carried to open the compressed alkali-cellulose. Later they are steeped to convert it back to the 15-35% proportion of alkali-cellulose. The solution is let to age to a certain amount of time, which is a major factor affecting the DP and polymer chain length of cellulose polymer, viscosity, and final yarn properties. (Kotek, 2007)

Xanthation process is carried on the alkali cellulose solution by dissolving it with carbon disulphide (CS_2). This process forms cellulose xanthate solution, which is a yellow viscous solution of viscose. The cellulose xanthate solution, after mixing, filtration and ripening, is extruded through a spinneret and wet-spun in a solution of sulphuric acid. Post spinning treatment in sulphuric acid recovers most of the CS_2 present in the fibre. The rest of the chemicals is just let out to effluent treatment plants.

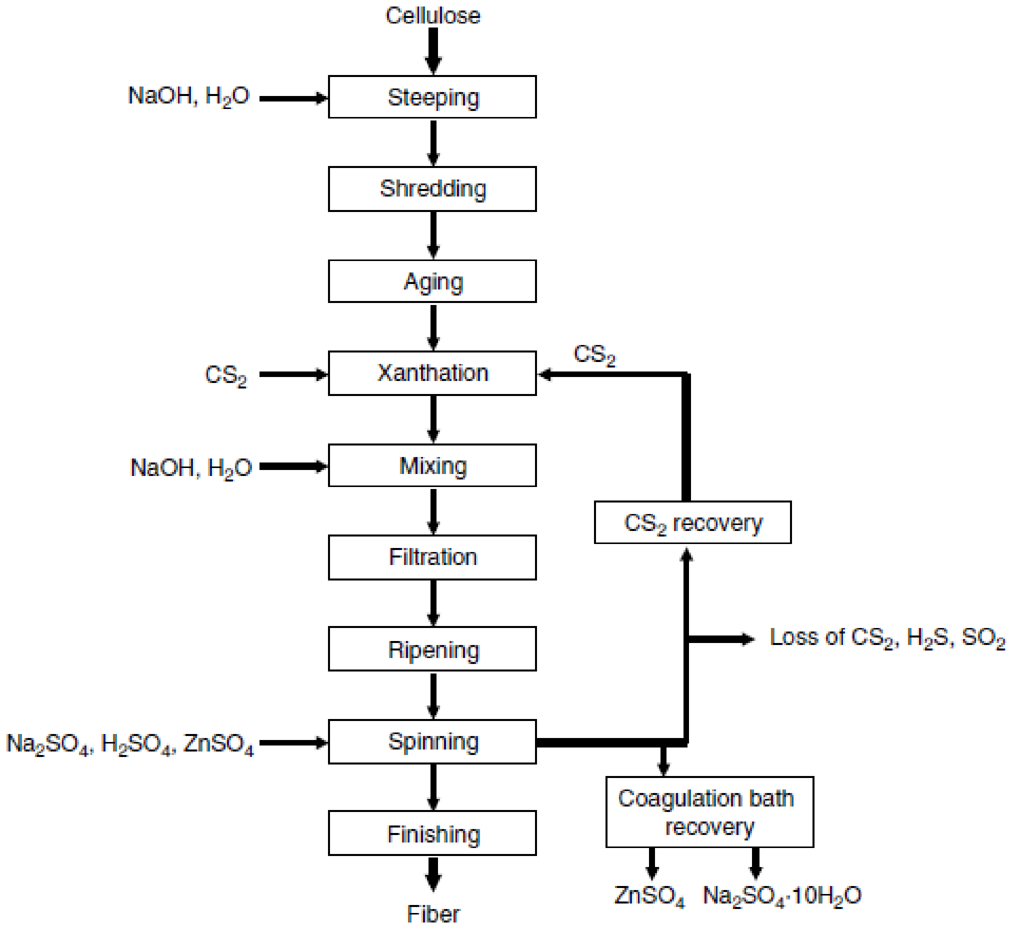

Figure 11 Process flow of viscose fibre making process with inflow and outflow chemicals. (Kotek, 2007, p. 677)

About 70% of the carbon disulphide used is only recovered, and the rest is converted into sulphuric acid for the next processes. Viscose in this sense is less sustainable and less eco-friendly, since the chemical recovery is lower than lyocell. Also the chemicals used in viscose process are mostly toxic.

The chemicals used in viscose process are,

- 17-19% aqueous sodium hydroxide
- Carbon disulphide
- 80 g/l of sulphuric acid
- 150-300 g/l of sodium sulphate
- 10-20 g/l of zinc sulphate

Viscose process has a lot of processes in the fibre forming like alkalization, pre-ageing, xanthation, ageing, desulphurising, and carbon disulphide recovery. Refer to Figure 12. The effluent water from viscose process could possibly contain the following

- Carbon disulphide, CS_2
- Hydrogen sulphide, H_2S
- Sulphur dioxide, SO_2
- Zinc sulphate, $ZnSO_4$
- Sodium sulphate, $NaSO_4$

All these possible effluent chemicals from viscose process contain sulphur, which is very toxic in nature. Hence the effluent from viscose process must be highly controlled and treated before letting out to the outer environment. Sulphur containing effluents make harm to the ground and water bodies if not treated properly. Effluent treatments increase substantially the production costs/expenditures in the viscose processes, and also the investments required for effluent treatment are also expensive. So many companies in the Block 2, 3, and 4 countries, where the importance to the environment comes after the monetary/economy, don't support installing effluent treatments. This is the biggest concern for viscose fibre production system in the block 2, 3, and 4 countries.

4.5.2. Lyocell process

Lyocell is one of the most important non-viscose rayon processes. Other non-viscose rayon processes for example are Akzo process, carbamate process, and the Cupro process. Lyocell process uses aqueous NMMO solution for dissolving cellulose. NMMO is a polar solvent which forms hydrogen bonds with the hydroxyl groups in cellulose polymer, and thus enhancing the dissolution of cellulose.

The lyocell process is a very simple process. Cellulose in the form of pulp is dissolved in hot NMMO (*N*-Methylmorpholine-*N*-oxide) with water solution. The maximum concentration of cellulose achieved in a NMMO solution is about 23%, which was possible by subsequently adding NMMO solution and removing water. (Kotek, 2007) The resulting solution is a highly viscous solution similar to lye (a liquid from wood ashes). Hence the lyocell process and the fibre made from the process got their name as lyocell, which means lye of cellulose.

The spinning dope, solution of dissolved cellulose in NMMO, is extruded through a spinneret at high temperatures. High temperatures reduce the viscosity of the spinning dope, thereby facilitating easier extrusion of the fibres. The extruded fibres are later coagulated in water. The fibres are washed and removed off NMMO in the fibres. The fibres are spun after drying. NMMO is recovered later from the process effluents. (Kotek, 2007) Refer to Figure 12. The recovery potential of NMMO (process chemical) lyocell process is the highest of all the cellulosic fibre processes.

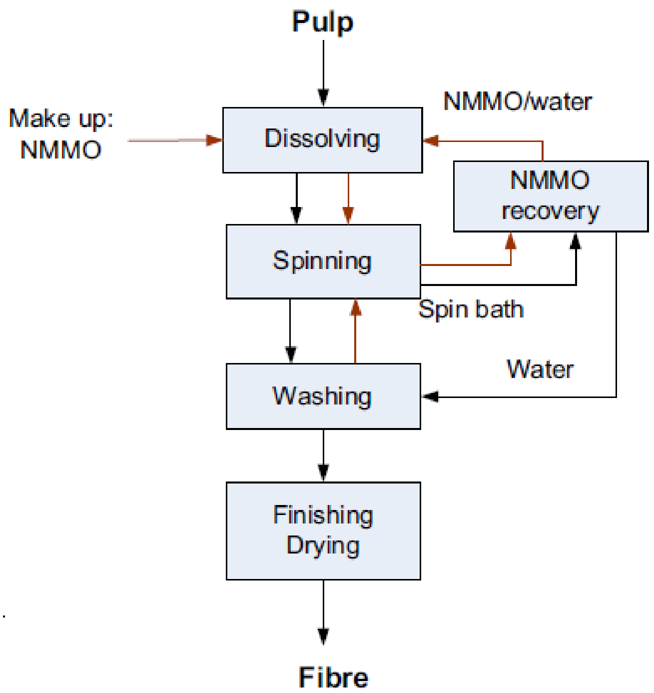

Figure 12 Process flow diagrams of lyocell fibre forming processes with the red arrows showing the flow of process chemicals. (Shen, Worrell, & Patel, 2010, p. 263)

Some of the advantages of lyocell process over viscose process are,

- Lyocell process is more eco-friendlier than viscose, as it has only few steps (shown in Figure 11 and Figure 12) in the production process and no toxic sulphur containing chemicals are used.
- The process is closed as both water and NMMO are recoverable and reusable.
- High process chemical recovery. More than 99% of the used chemicals in lyocell process can possibly be recovered and reused. Whereas in viscose only up to 70% of carbon disulphide is possible to recover from the process effluents.
- Lyocell have good mechanical properties and handle.

Lyocell process has the best production practice all over the world, owing to its eco-friendlier process design and non-/less toxic process chemicals. High hopes were being raised on the fibres produced from lyocell process to become the market leader in the future of cellulosic fibres.

4.5.3. Cellulose functionalisation

Cellulose functionalisation is the process of adding or improving properties to fibre molecules by modifying the chemical or physical structure or activating the fibre molecules. Refer to Figure 13. To explain, a solid filament fibre will have different properties if the fibre is formed with a hollow core, and adding reactive sites in polymer molecules also changes the properties of the polymer. Functionalisation opens doors for producing fibres of varied property range, from a single fibre producing process. For example, it is theoretically possible to functionalise the lyocell fibres to imitate the properties of viscose fibres.

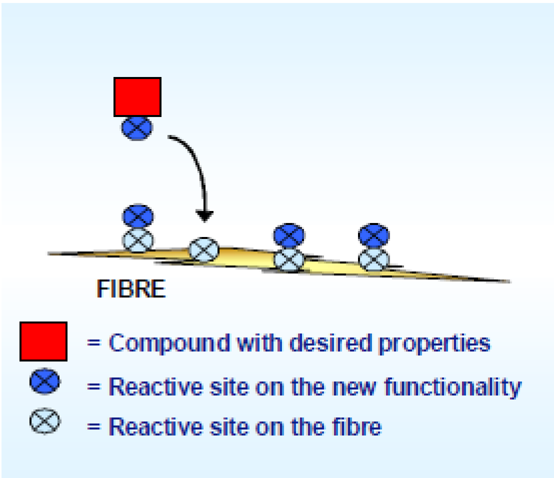

Figure 13 Schematic explanation of VTT's chemo-enzymatic functionalisation of cellulose polymers. (Suurnäkki, 2009, p. 67)

Cellulose functionalisation gives an option that only the fibres produced from most sustainable fibre production process could be produced, and those fibres could be functionalized to suit the requirement of the application for which the fibre will be developed. Lyocell process is the most eco-friendly process in cellulosic fibre making, and hence a lot of research on cellulose functionalisation has been carried on lyocell fibres. In a recent study researchers from Centre of Excellence for Polysaccharide Research argued that ILs (Ionic Liquids) offer greater possibilities for cellulose functionalisation than lyocell process. Since Ionic Liquids have higher chemical resistance, thermal stability, and better dissolving capacity. (Wendler, Kosan, Krieg, & Meister, 2009, p. 106) Researchers from University of Helsinki and Graz University of Technology successfully coupled "reactive" phenolic amines, "hydrophobicity" enhancing fluorophenols, and wood preservatives onto lignin model compound dibenzodioxocin. (Kudanga, Prasetyo, Sipilä, Nyanhongo, & Guebitz, 2009, p. 88) This further expands the options like phenol is a reactive and can possibly add a lot of other functionalizing elements, and fluorophenols could add hydrophobicity to the fibres.

VTT of Finland has developed another mode of functionalizing the cellulose fibres; it is by chemo-enzymatic functionalisation. Chemo-enzymatic functionalisation is carried in two processes, activation of fibre material and bonding of functional chemical component to the activated fibres. The functional chemical compound gives the needed properties' change in the cellulose fibres aimed. And the fibre activation increases the number of reaction sites for the functional chemicals to react on. (Suurnäkki, 2009)

5. APPLYING SUSTAINABILITY INDICATORS ON FIBRE PRODUCTION SYSTEMS OF CV, CLY, CO, AND PES

The sustainability indicators explained in 2.3 UN's working list of indicators of sustainable development has been applied on viscose, lyocell, cotton, and polyester fibre production systems. Out of all the indicators in the UN's working list about 42 indicators which are relevant to the fibre production systems included in this thesis are explained. If any two or more of these indicators not differing much on their own has been grouped under one explanation and also scored equally.

i_1 – Annual withdrawals of ground and surface water; i_2 – Ground water reserve

Water withdrawal is essential for human consumption, agriculture, and industrial activity in any area. But the importance is not the same for all the purposes. Human consumption should have the most priority in water consumption. But in less developed countries (Block 4) and developing countries (Block 2) due to lack of effective water management, the priority of water usage is unregulated.

Figure 14 classifies the countries of the world based upon their water availability and Figure 15 classifies based upon water withdrawal per inhabitant. Pakistan is one of the largest producers of cotton in the world with total production equalling 2.5 million tons i.e., about 10% of world's cotton production. Total available ground and surface water resource per capita is about 1000-1700 cubic meters/year (Figure 14), whereas the total water withdrawn for agriculture, domestic and industrial purposes was more than 1000 cubic meters/year (Figure 15). More than 90% of the water withdrawn in Pakistan is for irrigation purposes. Refer to Figure 16. Cotton is one of the major crops of Pakistan, increased about 26% from the year 1960. A major part of the water withdrawn goes for cotton cultivation, as 100% of the cotton fields in Pakistan are irrigated. (Kooistra & Termorshuizen, 2006). This situation seems alarming, as cultivating cotton though helps improving the economy of Pakistan, but it takes the water from the hands of the people.

Climate change also changes water availability around the world. The water availability is reduced more over the temperate regions, but increases generally over the polar and equatorial regions. As it can be seen in Figure 17 the water availability is reduced by 50% or under by 2100 in India. And India produces about 16% of the world's cotton.

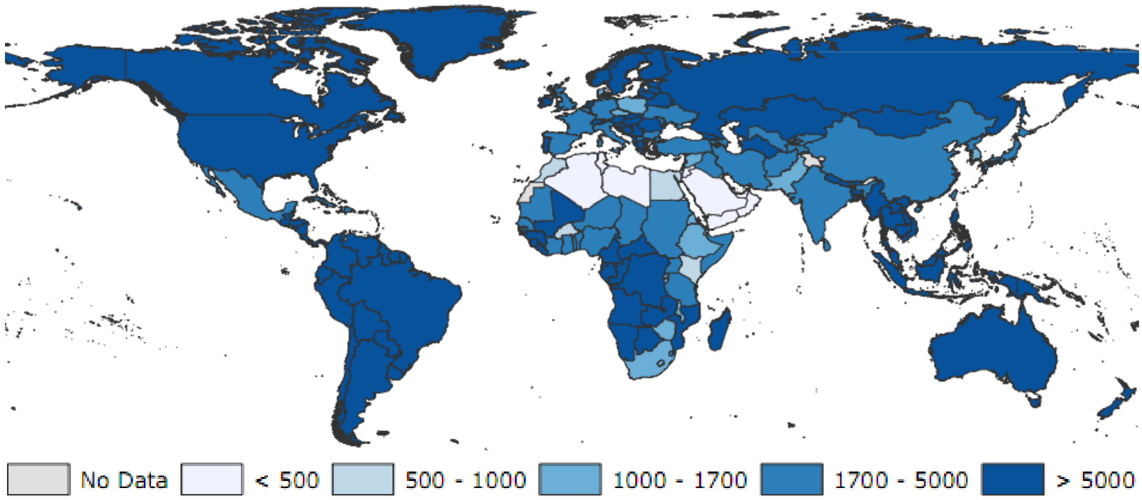

Figure 14 Total renewable surface water and ground water resources per inhabitant as on 2005 in cubic meters / year. (FAO's Aquastat, 2011)

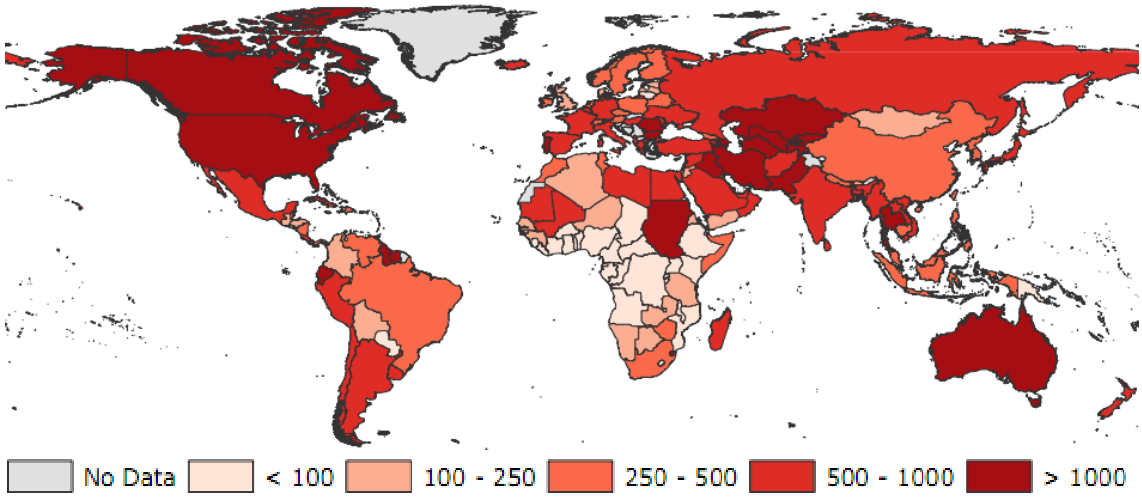

Figure 15 Water withdrawal per inhabitant for agricultural, domestic, and industrial purposes as on 2001 in cubic meters / year. (FAO's Aquastat, 2011)

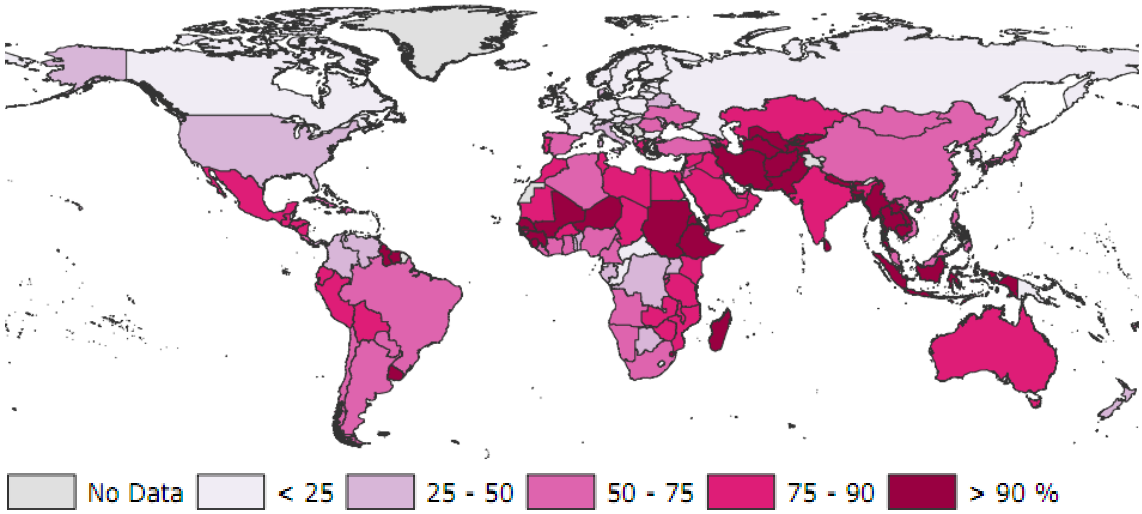

Figure 16 Percentage of agricultural water withdrawal in total water withdrawal for argriculture, domestic, and industrial use. (FAO's Aquastat - global maps, 2011)

Similar to Pakistan, the water scarcity will also be aggravated in countries like India and China in the future.

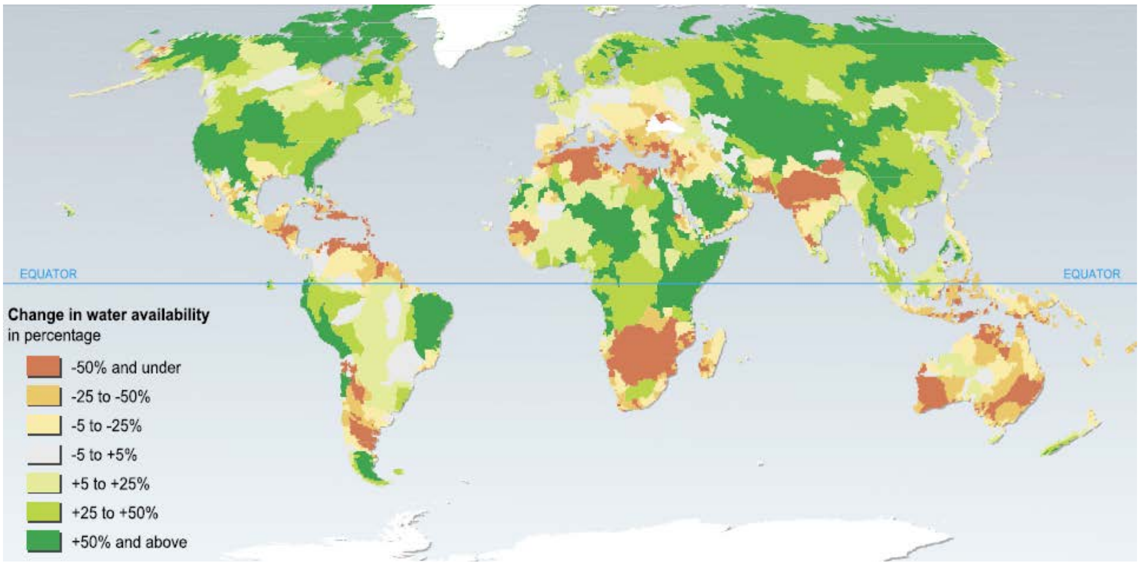

Figure 17 Graphical expression on the estimated changes in water availability by 2100. (Millennium Ecosystem Assessment, 2005)

Most of the Block 2, high population dense countries, experience the similar situation as that of Pakistan and India. Cotton cultivation is less sustainable in those countries. Also the fact, that 53% of cotton fields are irrigated consuming one-sixth of world's fresh water withdrawal, supports the argument. (Kooistra & Termorshuizen, 2006) The water needs for lyocell, viscose, and polyester decreases respectively, they get increasingly more sustainable all over the world.

i_3 – Wastewater treatment; i_{25} – Expenditure on waste management

Wastewater is produced where a civilization lives. Wastewater treatment is essential to prevent exploitation of the environment and water bodies. Both industrial and municipal wastewater must be let to the sewerage system and treated by treatment plants before letting it to the environment, mostly to the sea or river. Sewerage systems are common in Block 1 countries and urban areas of Block 2 and 3 countries. But it is not common in Block 4 countries and rural areas of Block 2 countries. In those areas municipal wastes are mixed with industrial wastes and let to the nearby water bodies like rivers, lakes and seas. This is a highly potential threat for health of the people living in those areas. For example in some parts of China where the wastewater-mixed-water is used for irrigation is reported to have caused health problems like enlargement of liver, cancer and increased congenital malformation rates, for the people living in those areas. (Smith, 2002, p. 3)

Figure 18 shows the amount of wastewater treated in different areas of the world. Block 1 country's dominant areas – North America and Europe, have the highest percentage of wastewater treated, 90% and 66% respectively. This is an indication that fibre production systems involving direct wastewater generation like viscose and lyocell and indirect wastewater generation like cotton and significantly also polyester are comparatively more sustainable in Block 1 countries. Block 2 countries are the most affected from wastewater hazards since the population density is very high, and potentially more people could get affected.

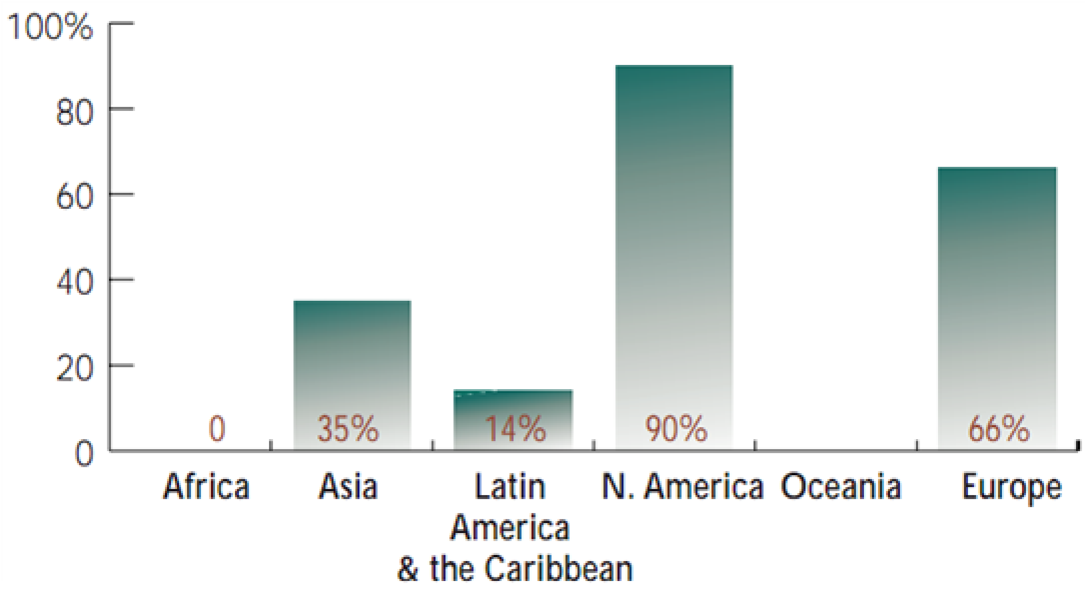

Figure 18 Median percentage of wastewater treated by effective treatment plants. (Lisa Schlein, 2001, p. 12)

i_{33} – Access to safe drinking water

World Health Organisation states that about 13% of the world's population doesn't have access to safe drinking water. And most of this population lives in Africa and South-East Asian countries dominated by Block 4 and 2 countries. Refer to Figure 20. Fibre production systems essentially involve water use and effluent water. So any fibre production system is less sustainable in Block 4 and 2 countries. (WHO & UNICEF, 2010)

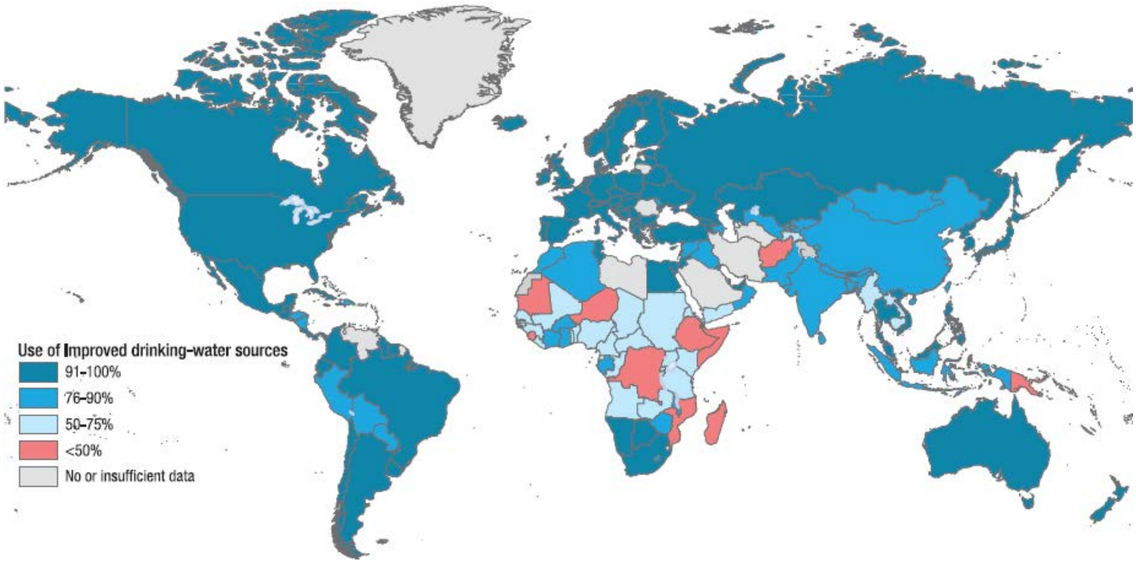

Figure 19 Worldwide use of improved drinking water sources as on 2008. (WHO & UNICEF, 2010)

The sustainability indicator scores for the indicators i_1, i_2, i_3, i_{25}, *and* i_{33} are explained in Table 12, where each fibre production system-country combination generates a score as shown in the body of the table.

Table 12 - i1 – Annual withdrawals of ground and surface water; i2 – Ground water reserve; i3 – Wastewater treatment; i25 – Expenditure on waste management; i33 – Access to safe drinking water

Fibre production system	**Indicator(s)**	**Block 1 = 1**	**Block 2 = 4**	**Block 3 = 2**	**Block 4 = 3**
CV = 3	i_1, i_2, i_3, i_{25}, i_{33}	3	12	6	9
CLY = 2	i_1, i_2, i_3, i_{25}, i_{33}	2	8	4	6
CO = 4	i_1, i_2, i_3, i_{25}, i_{33}	4	16	8	12
PES = 1	i_1, i_2, i_3, i_{25}, i_{33}	1	4	2	3

PES production, since doesn’t involve water intensive processes than any other fibre production processes, remains the most sustainable (score 1). CLY and CV though are less water intensive than cotton, but have higher scope for polluting the water bodies. Most CLY and CV fibre manufacturing companies reduce and reuse the water usage. And so the threat of water pollution is considerably reduced. So it can be said in every way, cotton is the most unsustainable (score 4) when compared with all these fibres. Planted forests in tropical regions like India are occasionally irrigated, at least in the earlier stages of the tree growth, whereas in the temperate forests there is no need for irrigation. This refers to the fact that CLY uses mainly dissolving pulps from tropical woods, whereas CV uses dissolving pulps from both tropical and temperate woods. So CV is more sustainable than CLY, therefore the score for CV is 3 and for CLY is 2.

i_4 – Land use change; i_5 – Changes in land conditions

About 10% of the world’s land is arable and is used for cultivation. There’s a sharp increase in the amount of land used for cultivation in the last few decades to feed the growing population of the world. Refer to Figure 21. Most of the lands converted to agricultural farms were naturally forests. A good example for this is the situation prevailing in Brazil, where the rain forests of the Amazon were converted to soy and cotton fields. Brazil accounts for about 5% of the world’s cotton production.

Clearing forests for agricultural purposes is less sustainable since the total carbon absorbed in a unit agricultural area is lower for the same unit forest area. And also it decreases the ecological diversity in that area, as explained in i_{19} – Threatened species as a percent of total native species. The other environmental impacts and changes in land conditions will be dealt under the subsequent indicators.

i_6 – Satellite derived vegetation index

Satellite derived vegetation index provides useful information on the percentage of the vegetated land under cultivation. The lands under cultivation are susceptible to or have already been affected by environmental impacts like:

- Forest clearing
- Salinization from irrigation
- Soil erosion
- Nitrogen and sulphur deposits from pesticides and fertilizers
- Greenhouse gases emissions from agricultural fields like methane

Satellite derived vegetation index and percentage of forest area in total area of a country as shown in Figure 21 and Figure 20 respectively gives an idea on deforestation for agricultural purposes.

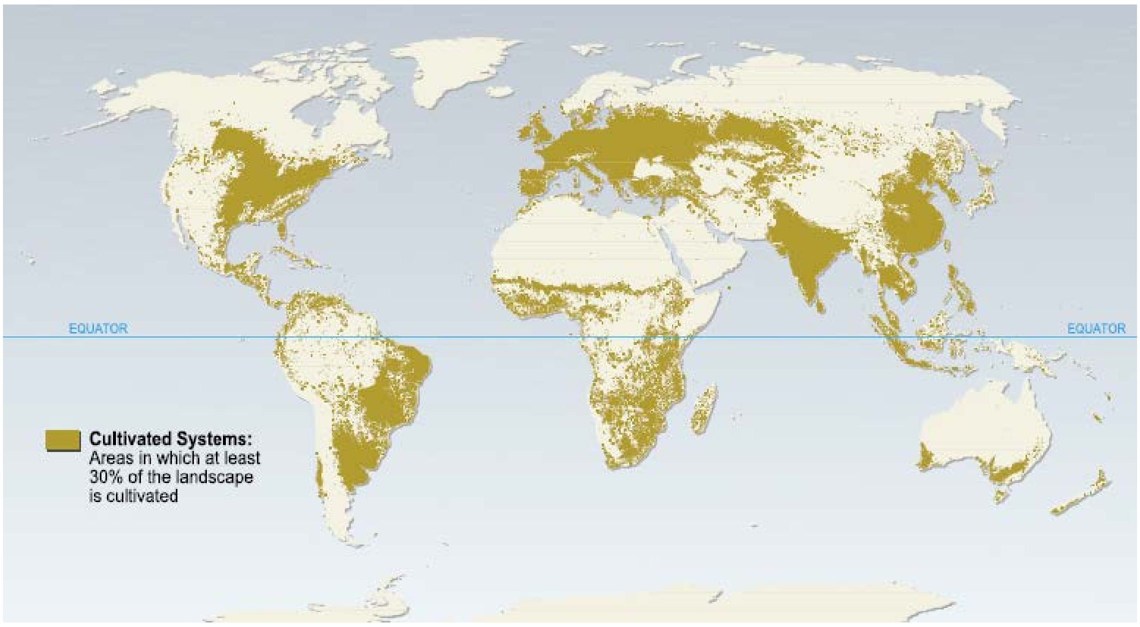

Figure 20 Land area under cultivation, 2000. (Millennium Ecosystem Assessment, 2005, p. 52)

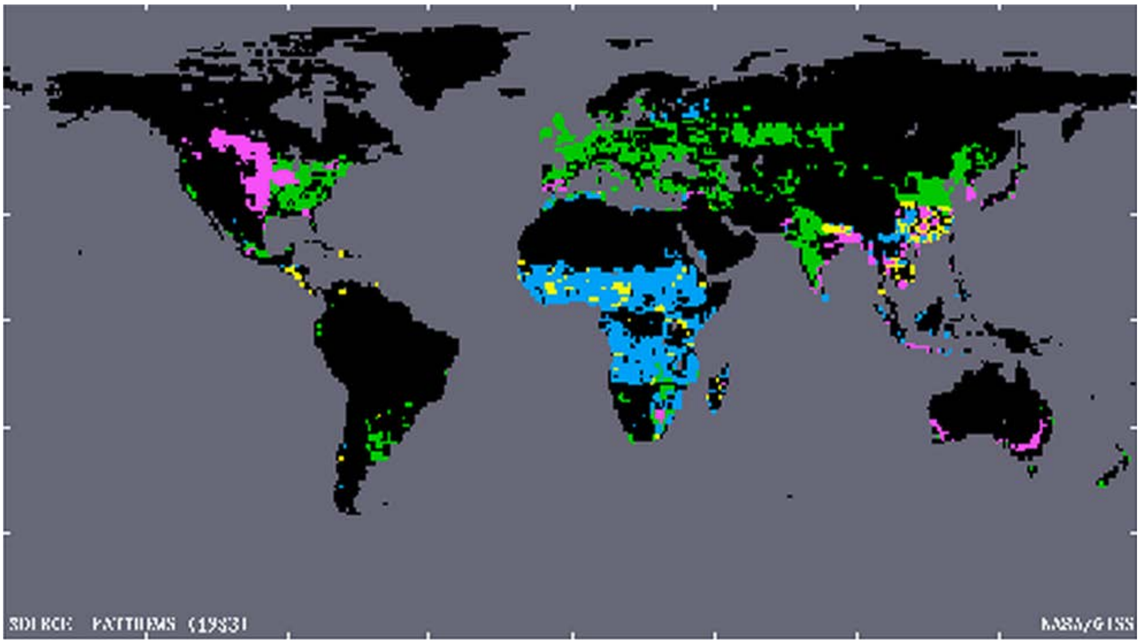

Figure 21 Global land use for cultivation, with different colours expressing cultivatition intensity like 0-20% cultivated - Black, 20-50% cultivated = Yellow, 51-75% cultivated = Green, 76-100% cultivated = Pink. (Hansen, 1983)

i_7 – Land affected by desertification

Desertification is a serious concern in today's world. It is not natural expansion of deserts as it is generally thought to be. But desertification is degradation of land by climatic variations and anthropogenic activities. Desertification affects nearly one billion people and one quarter of the world's land. And is the reason for much of the migration and poverty in the Block 2, 3, and 4 countries. Desertification on earth takes away 2 billion tons of topsoil from the land surface. Desertification affects the vegetation and results in drought, with each drought cycle desertification increases resulting in drought again. In Africa about 36 countries are affected by drought and desertification. Asia has the largest amount of land affected by desertification, which amounts under 1.4 billion hectares. China, Afghanistan, Mongolia, Pakistan, and India are the most affected in Asia. In Latin America Mexico is the most affected country from desertification, where 85% of the desertification is caused by water erosion. Removal of vegetation and unsustainable agricultural practice alone makes up to 70% of desertification in the world. (UNEP, 1997)

Block 2, 3, and 4 countries are the most affected. And apparently countries with high population density, Block 2, are affected the most. Hence the fibre production systems of cotton are less sustainable in Block 2, 3, and 4 countries.

Table 13 - i4 – Land use change; i5 – Changes in land conditions; i6 – Satellite derived vegeta-tion index; i7 – Land affected by desertification

Fibre production system	**Indicator(s)**	**Block 1 = 4**	**Block 2 = 3**	**Block 3 = 2**	**Block 4 = 1**
CV = 2	i_4, i_5, i_6, i_7	8	6	4	2
CLY = 3	i_4, i_5, i_6, i_7	12	9	6	3
CO = 4	i_4, i_5, i_6, i_7	16	12	8	4
PES = 1	i_4, i_5, i_6, i_7	4	3	2	1

Cultivation is one of the essential human activities, but it also affects all the above discussed four indicators of sustainability (i4, i5, i6, and i7). Cultivated soils are usually loose and prone to soil erosion by wind and water. Some of the consequences of soil erosion are landslides in hilly areas, less fertile soil, dust storms, and higher dissolved particles in rivers. Tornadoes happen only in lands of high cultivation. For a block country, these sustainability indicator score proportionally to the area of the land cultivated, i.e., higher the intensity of cultivation lesser is its sustainability. Hence the block country scores (4, 3, 2, 1) are given respectively. Cotton is the only fibre discussed in this work that is cultivated, hence naturally it scores the least (score = 4). As it has been discussed before that lyocell is the fibre made from the wood pulps produced in tropical countries and viscose is made from both tropical and temperate, so it can be said lyocell has the second highest impact on the sustainability (score = 3) and followed by viscose (score = 2). Polyester naturally is the most sustainable with regard to sustainability indicators concerned.

i_8 – Use of agricultural pesticides; i_9 – Use of fertilizers

Agricultural pesticides used in cotton cultivation accounts to about 11% of world's pesticides use in agriculture. But cotton is grown only on 2.4% of world's arable land. Especially in developing countries it is estimated that around 50% of all the pesticides used in agriculture is applied for cotton cultivation. This situation is very harmful for the farmers working on cotton farms. It has been estimated that 40,000 lives are lost due to pesticide application activities, and 50% of the cotton growers and workers suffered from chronic disorders. The rest of deaths accounted from mixing of pesticide into water stream used for consumption by the people. (Kooistra & Termorshuizen, 2006, p. 15) Wood cultivation doesn't require pesticide.

Fertilizers are a must for cotton cultivation. In organic farming natural fertilizers like animal manure, green crops, and compost are used. But still 80% of the cotton cultivation in the world is carried by conventional methods. (Kooistra & Termorshuizen, 2006) Block 2, 3, and 4 countries are the most affected from the cotton cultivation, due to their high population density and increasing use of fertilizers, followed by Block 1. Refer to Table 14.

Following the discussions above, CO can be said the most unsustainable (score = 4). Though the practice of organic farming has been gaining popularity but it would take many years to become as a conventional farming practice, and it cannot be taken into account as of now.

Wood cultivation like beech plantations are not fertilized nor irrigated, but the eucalyptus plantations are fertilized with small amounts of nitrogen fertilizers. The fertilizer use in wood growing is significantly low. (Shen, Worrell, & Patel, 2010, p. 262) Beech plantations are mostly present in temperate regions and eucalyptus plantations are mostly present in tropical regions. It has also been the case for all other wood plantations that the tropical plantations use fertilizers and pesticides and the temperate plantations do not. Since the wood for CLY production comes from tropical woods and CV is produced from both temperate and tropical woods, CV is considered to be more sustainable than CLY in this regard (CV score = 2, CLY score = 3).

The use of pesticides and fertilizers cannot be eliminated with the current practice of agriculture all over world. More the use of fertilizers and pesticides is regulated in a Block country, the higher the sustainability of that Block country. Hence it can be said that the Block 1 are the most sustainable, and Block 3, 2, and 4 countries are less sustainable over the other respectively.

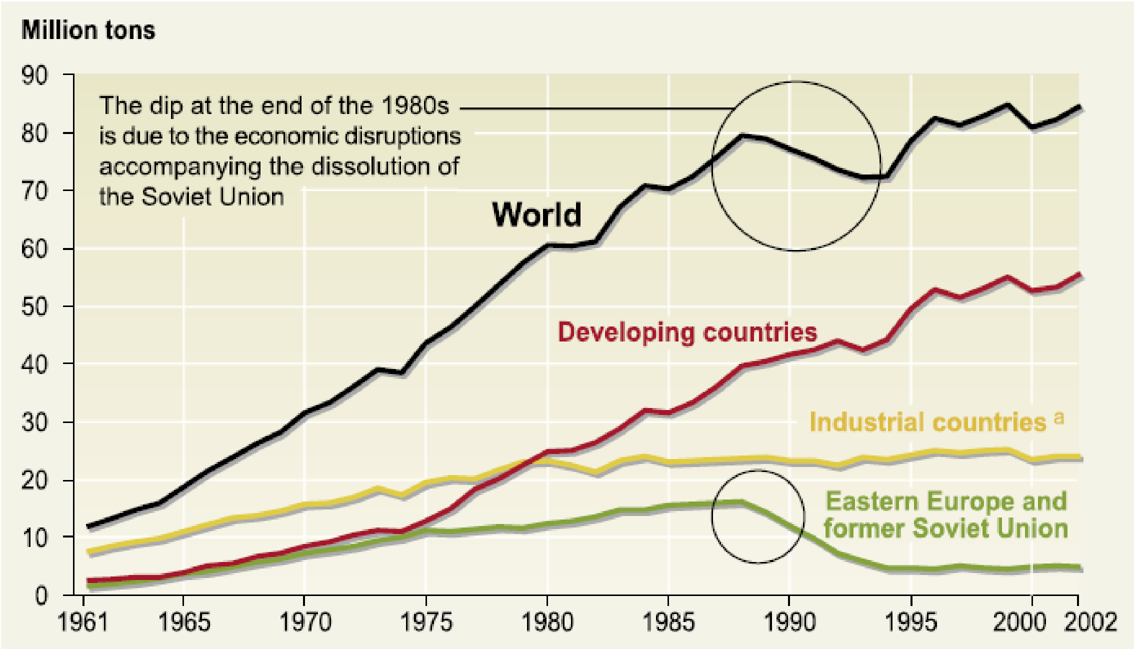

Figure 22 Trends in the use of nitrogen fertilizers from 1961-2001 in million tons. [a] – excluding Eastern Europe and former Soviet Union. (Millennium Ecosystem Assessment, 2005)

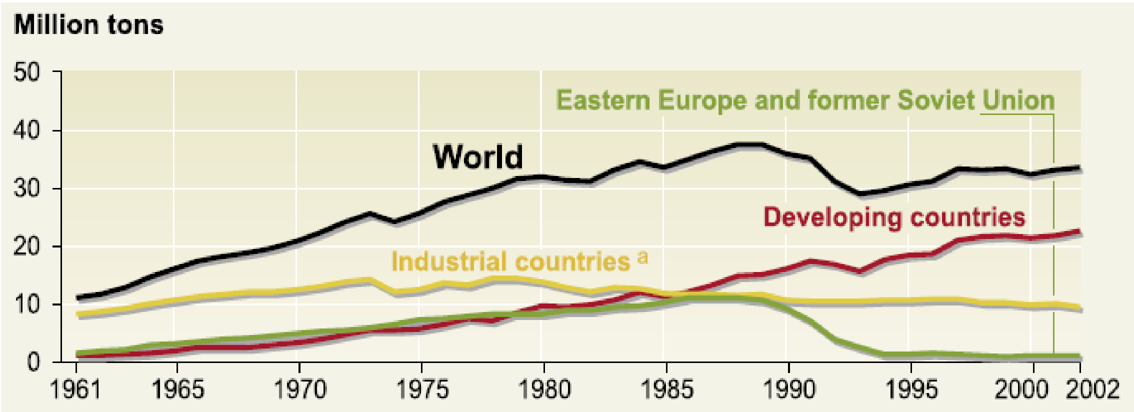

Figure 23 Trends in use of phosphate fertilizers from 1961-2001 in million tons. [a] - excluding Easter Europe and Soviet Union. (Millennium Ecosystem Assessment, 2005)

Table 14 - i8 – Use of agricultural pesticides; i9 – Use of fertilizers

Fibre production systems	Indicator(s)	Block 1 = 1	Block 2 = 3	Block 3 = 2	Block 4 = 4
CV = 2	i_8, i_9	2	6	4	8
CLY = 3	i_8, i_9	3	9	6	12
CO = 4	i_8, i_9	4	12	8	16
PES = 1	i_8, i_9	1	3	2	4

i_{10} – Irrigation percent of arable land; i_{13} – Area affected by salinization and water logging

Irrigation is supplying of water to cultivable lands for agriculture. Basically irrigation involves flowing of water to the lands where they are not naturally flown. And the irrigated water can be either surface water or ground water. This implies three adverse effects on the soil and land quality. Like,

- Land salinization,
- Water logging, and
- Soil erosion by water flow.

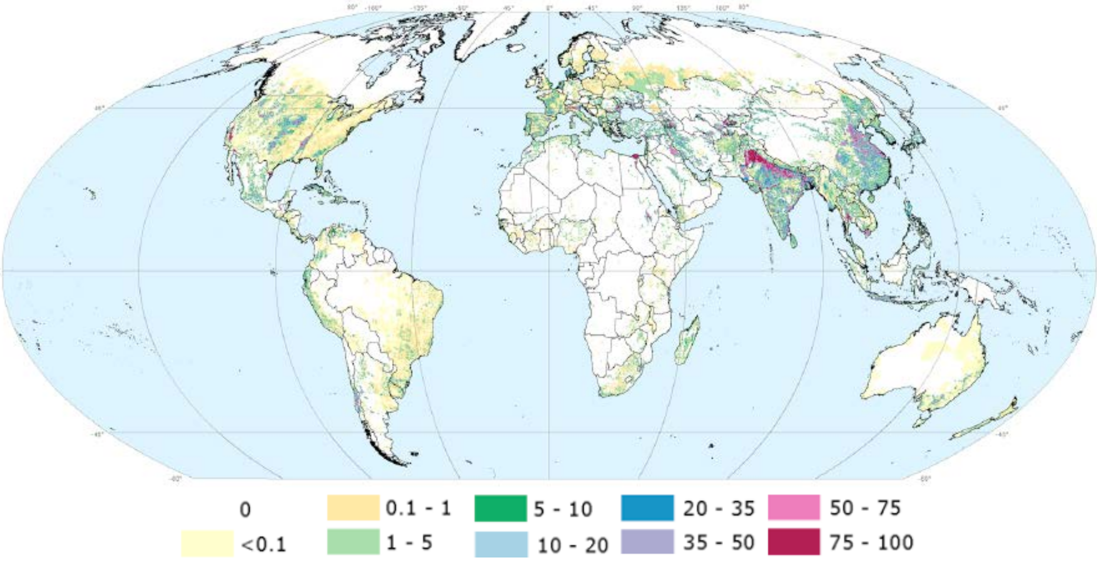

Figure 24 Showing the global area under irrigation in percentage of total land area during 1997 to 2002. (FAO's Aquastat - Irrigation map, 2007)

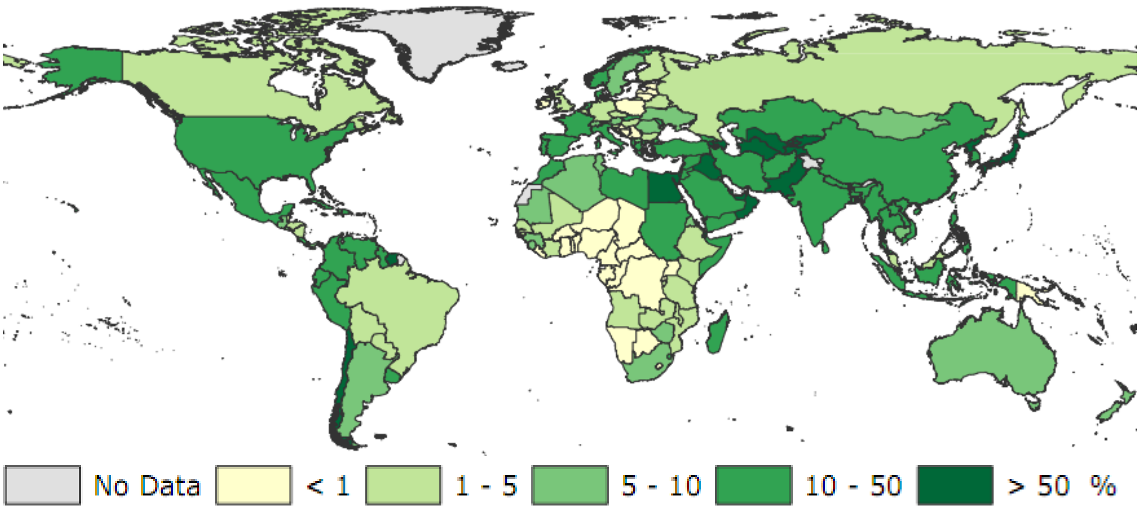

Figure 25 Percentage of cultivated land under irrigation during 2003. (FAO's Aquastat - global maps, 2008)

Salinization occurs when water carrying sediments and salts are irrigated into the fields. Such waters deposits soluble salts and insoluble salts like calcium carbonate into the soil. Depositions of insoluble salts resist water flow into the soil, thereby resulting in water logging. Excess usage of ground water would result in more salty ground water, depositing salts again to the ground. Excess water flow through the lands, in case of irrigating surface water, erodes the lighter soil particles and salts from the soil, thereby reducing the nutrient content of the soil.

Irrigation is a good and sustainable practice for agriculture, but it shouldn't be overdone. Parts of China, India, and most of Pakistan have more than 50% of their cultivable lands under irrigation. Refer to Figure 24 and Figure 25. This would pose a threat to land degradation by any of the above discussed effects in the future. Planted forests are not irrigated usually. So they are more sustainable than cotton cultivation. The irrigated percent of the total arable land is lesser in Block 1 countries and so Block 1 countries are more sustainable to have the fibre production systems.

Table 15 - i10 – Irrigation percent of arable land; i13 – Area affected by salinization and water logging

Fibre production systems	Indicator(s)	Block 1 = 1	Block 2 = 4	Block 3 = 2	Block 4 = 3
CV = 2	i_{10}, i_{13}	2	8	4	6
CLY = 3	i_{10}, i_{13}	3	12	6	9
CO = 4	i_{10}, i_{13}	4	16	8	12
PES = 1	i_{10}, i_{13}	1	4	2	3

i_{10} and i_{13} share almost the same sustainability indicator scores as i_8 and i_9 expect that Block 2 scores worse than Block 4 countries since the effects of irrigation is much more prevalent in Block 2 countries. The scores are shown in Table 15.

i_{11} – Energy use in agriculture

A more sustainable agriculture practice is to have less energy use in agriculture. Block 4 countries dominated Africa uses relatively least energy for agriculture production, and hence agriculture is more sustainable in Africa. For region specific details on energy consumption in agriculture refer Table 16.

i_{12} – Arable land per capita; i_{14} – Agricultural education

All these indicators express sustainable agriculture practice. A more sustainable agriculture practice is to have more arable land per capita and higher agricultural education. Arable land per capita is shrinking year by year by two reasons, firstly growing population needing more land for cultivation and secondly climate change. In 1970 arable land per capita was about 0.38 hectares, but in the year 2000 it was about 0.23 hectares. And it has been estimated to go down to 0.15 hectares per capita by 2050. Asia has realized 94% of potential arable lands to cultivation, but sub-Saharan Africa has realized only 22% of potential arable lands. (FAO, 2011) Agricultural education increases the agricultural output and also promotes sustainable agriculture. Block 2, 3, and 4 countries' problems with agricultural sustainability, like less sustainable cotton cultivation, cannot be resolved without agricultural education. Refer to Table 16.

Table 16 - Energy use in agriculture as on 1982. (FAO, 2000)

Region	Energy per hectare of arable land (kgoe/ha)	Energy per tonne of cereal (kgoe/t)	Energy per agricultural worker(kgoe/person)
Africa	18	20	26
Latin America	64	32	286
Far East	77	43	72
Near East	120	80	285
All developing countries average	96	48	99
All industrialized countries average	312	116	3294
World average	195	85	344

Table 17 - i11 – Energy use in agriculture

Fibre production systems	Indicator(s)	Block 1 = 4	Block 2 = 3	Block 3 = 2	Block 4 = 1
CV = 3	i_{11}	12	9	6	3
CLY = 2	i_{11}	8	6	4	2
CO = 4	i_{11}	16	12	8	4
PES = 1	i_{11}	4	3	2	1

In the point of view of Energy use in agriculture the most sustainable agriculture is in the Block 4 countries and reduces successively moving to Block 1 countries, whereas in the point of view of Arable land per capita and Agricultural education Block 1 countries do the best and reduces successively moving to Block 4 countries. The scores are shown in Table 17 and Table 18.

PES is the most sustainable and CO is the most unsustainable for natural reasons. But CLY scores better than CV in Energy use in agriculture, since the wood pulp used for CLY is made from trees grown only in Block 2 and 4 countries, hence it is assumed the energy consumed is lesser, than for producing wood pulp for CV including Block 1 countries. And for the same above argued reason, CV scores better than CLY for Arable land per capita and Agricultural education.

Table 18 - i12 – Arable land per capita; i14 – Agricultural education

Fibre production systems	Indicator(s)	Block 1 = 1	Block 2 = 2	Block 3 = 3	Block 4 = 4
CV = 2	i_{12}, i_{14}	2	4	6	8
CLY = 3	i_{12}, i_{14}	3	6	9	12
CO = 4	i_{12}, i_{14}	4	8	12	16
PES = 1	i_{12}, i_{14}	1	2	3	4

i_{15} – Wood harvesting intensity; i_{16} – Forest area change

World's forests cover about 31% of the total land area i.e., over 4 billion hectares, which is about 0.6 hectares per capita. (FAO, 2010) With the growing current population this per capita figure is bound to decrease further. Deforestation rate has generally been reduced to the rate of 13 million hectares per year by 2010 from 16 million hectares per year by 1990. Though large scale planting of trees and planted forests are increasing day by day, the deforestation rate remains a major threat for the environment. (FAO, 2010)

Figure 26 and Figure 27 shows the total forest area by total land area and annual change in forest area during 2005 to 2010 of the world countries respectively. Block 1 countries, like Russia, Northern European countries, and North American countries have high percentage of forests comparatively. Only the equatorial countries have equal to or more forest area than the Block 1 countries. The equatorial countries are mostly Block 2 and Block 3. Block 1 countries actually gain forest area every year from 50 000 to 500 000 hectares per year. Whereas, Block 2 and Block 3 countries loose the same amount of forest area every year, the only exception here is China having the highest growth in forest area in the world. (FAO, 2010) The equatorial countries are also tropical countries, which are bio-diversity hotspots, so reduction in forest areas is fatal for thousands of species habituating there.

The characteristics of wood removals from the forests are shown in Figure 28,which shows a clear differentiation between Block 1 countries (Europe, and North America) and the others, that the wood removals for industrial purposes is comparatively very high in Block 1 countries. Wood removals for wood fuel purposes are less sustainable, since it exploits a valuable commodity like wood just for energy needs.

Considering the above reasons the scores for the indicator, i_{15} – Wood harvesting intensity is as given in the table below. Wood harvesting is least sustainable in Block 2 countries like India, Brazil, and Indonesia, since the land area per capita is low on a whole and generally they have tropical rain forests. Wood harvesting in less developed countries is comparatively more sustainable since they provide livelihood for certain population.

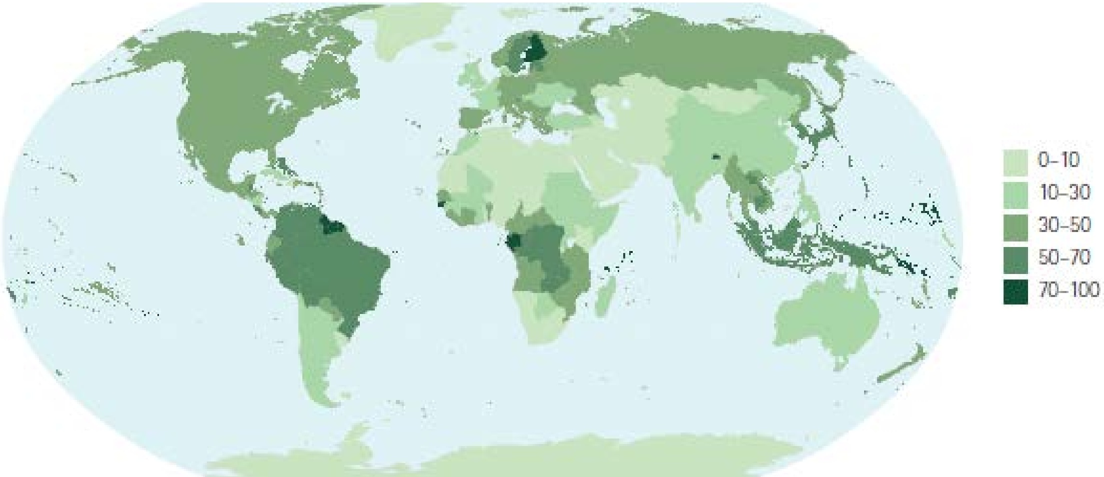

Figure 26 Forest area as a percentage of total land area by country during 2010. (FAO, 2010, s. 3)

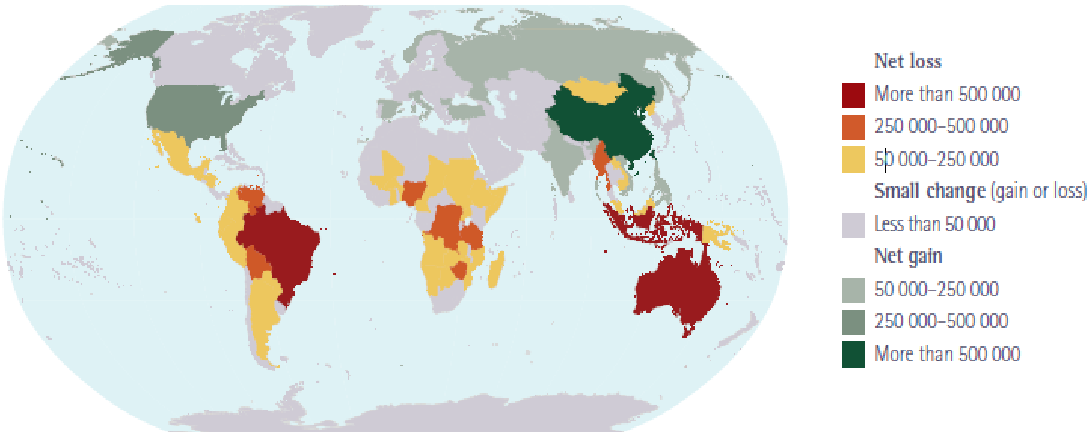

Figure 27 Annual change in forest area by country during 2005 to 2010 in hectares/year. (FAO, 2010, p. 4)

Figure 28 Wood removals for industries and wood fuel during 1990 to 2005 in million metric cubes. (FAO, 2010, p. 7)

i_{17} – Managed forest area

Of the 31% of the forest area land in total land area of the world, primary forests constitute only up to 36%, naturally regenerated forests up to 57% and planted forests up to 7%. Primary forests are basically naturally occurring forests and have not been altered by the recent anthropogenic acts, whereas regenerated forests are influenced by human activity. Refer to Figure 29.

Africa has the least primary and planted forests, this is an indication that the forest resources of Africa has been over exploited and poorly managed. Though Asia has one of the least amount of primary forests, but have the largest amount of planted forests, this can be explained with the fact that Asia is home to more than half of the world's population and a very long history of human activity. South America has the highest amount of primary forests, and it has to be preserved for maintaining the bio-diversity.

The bio-diversity can only be preserved in primary forests, since the destruction of a species habitat once will destroy the whole species. And when a forest is destroyed it takes hundreds of years for the forest to grow back to its primary state, as lot of species in an ecosystem are interdependent and they can only thrive if also their dependents thrive. Naturally regenerated forests will change to primary forests very gradually with no human activity.

The primary forests by definition are not managed rather they are only monitored, whereas the planted forests or regenerated forests are managed for production and other purposes. For example, Europe has the largest forest area under management, refer to Figure 30, but the forestry products are not the main produced goods of many European countries. Apart from forest products production, forest areas have been managed for many reasons, as shown in Figure 31. Forest management accounts only 30% for production, the rest being managed for conservation, protection, and other purposes.

Forest ownership patterns are important indicators of forests management. High public owned and managed forests are easier to monitor and control. And so it is also easier to control deforestation in those forests. Exceptions being Africa, where the public owns most of the forests but still the deforestation is high refer Figure 27 and Figure 32.

i_{18} – Protected forest area as a percent of total forest area; i_{20} – Protected area as a percent of total area

Protection of forest areas is usually done by converting the forest areas into national parks, reserved forests, wilderness areas, and also for conservation of certain animals, water bodies, soil from erosion, or even the night sky.

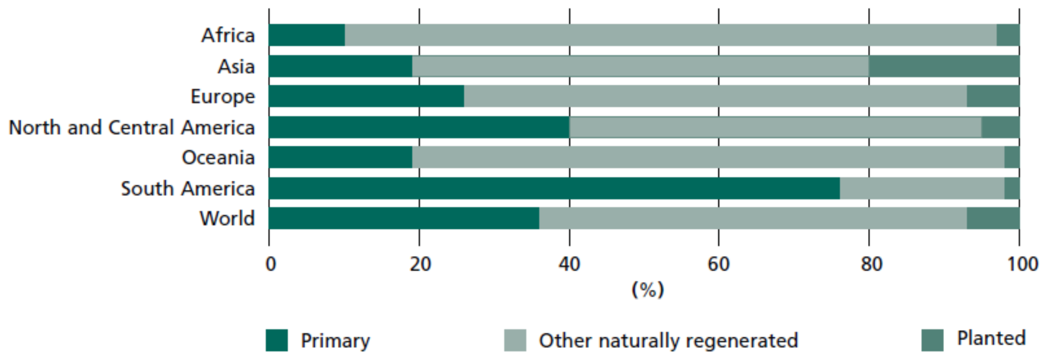

Figure 29 Characteristics of world's forests, 2010. (FAO, 2010, p. xviii)

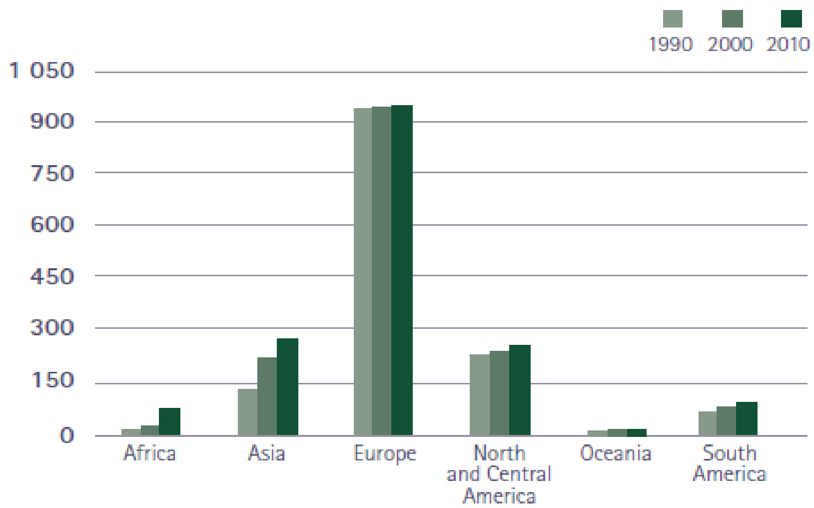

Figure 30 Total managed forest areas, 1990 to 2010 in million hectares. (FAO, 2010, p. 10)

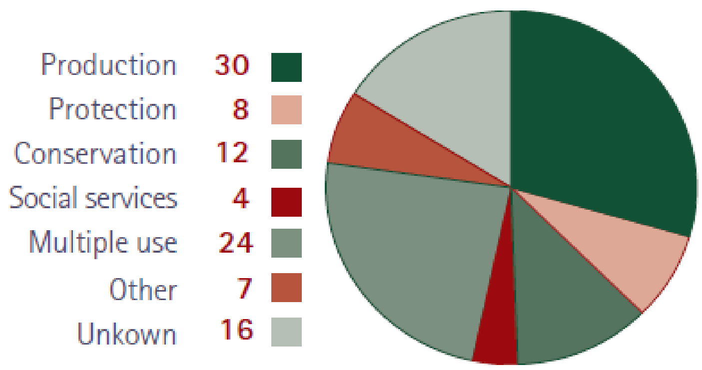

Figure 31 Designated functions of world's forests in 2010 (%). (FAO, 2010, p. 10)

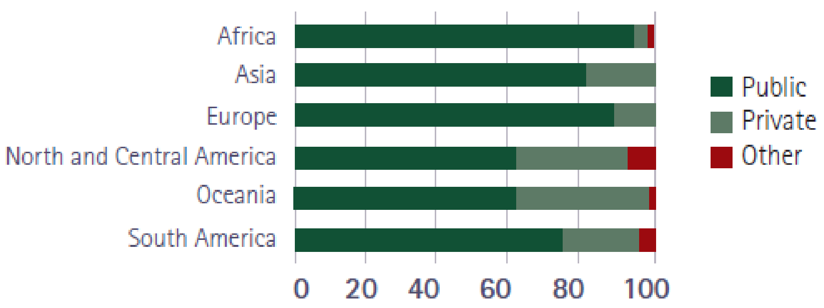

Figure 32 Forest ownership patterns, 2005 (%) (FAO, 2010, p. 10)

Legally protecting the forests conserves bio-diversity and prevents deforestation, therefore enhancing sustainability. The Block 1 countries' seem less sustainable in the view of this sustainability indicator (i_{18} – Protected forest area as a percent of total forest area). Refer to Figure 33.

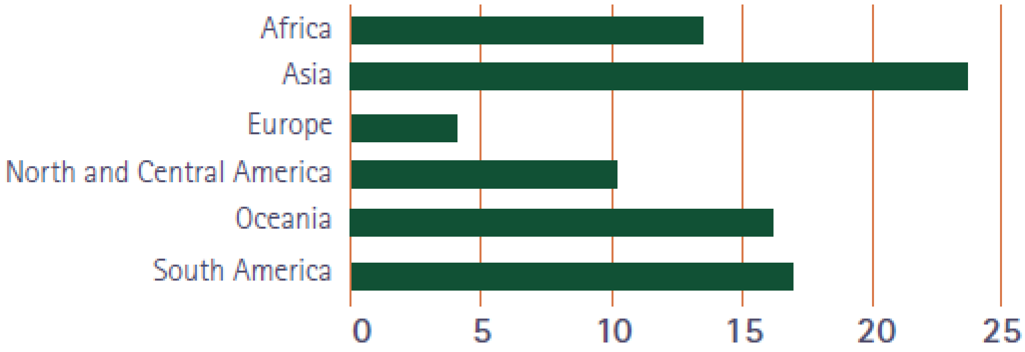

Figure 33 Proportion of legally protected forests by 2010 (%). (FAO, 2010, p. 6)

i_{19} – Threatened species as a percent of total native species

The Millennium Ecosystem Assessment 2005 classifies the whole ecosystem of the world into 14 biomes, as explained in Figure 34. North America, Russian Federation, Europe, Australia and New Zealand which belong to the Block 1 countries constitute the Noarctic, Palearctic and Australasian parts of the world, and they are mostly temperate. These parts are predominant of all kinds of temperate forests and grasslands, Tundra vegetation, and Boreal forests. The rest of the biomes – Neotropical, Afrotropical, Indo-Malay, and Oceanic are mostly populated by Block 2, 3, and 4 countries, which are situated around the equator and are mostly tropical.

The temperate and the tropical biomes of the world differentially occupies the lesser and higher richness of species richness and family richness of the biomes in the world respectively. Figure 36 gives an estimation of the number of species and families of species present in the all the 14 biomes of the world. It can be clearly seen that the temperate (Block 1) and tropical (Block 2, 3, and 4) occupy the higher and lesser part of the species number on the scale. Thus it can be understood that any harm to the ecosystem or forest in a tropical biome makes more harm to the biodiversity of the world species when compared to a tropical biome.

The tropical and sub-tropical moist broadleaf forests which form most of the Block 2, 3, and 4 countries have the highest percentage of threatened vertebrate species rather than the temperate biomes. It is clearly explained in Figure 35. Vertebrate species include all the species with a vertebral column or a back bone like mammals, birds, and reptiles.

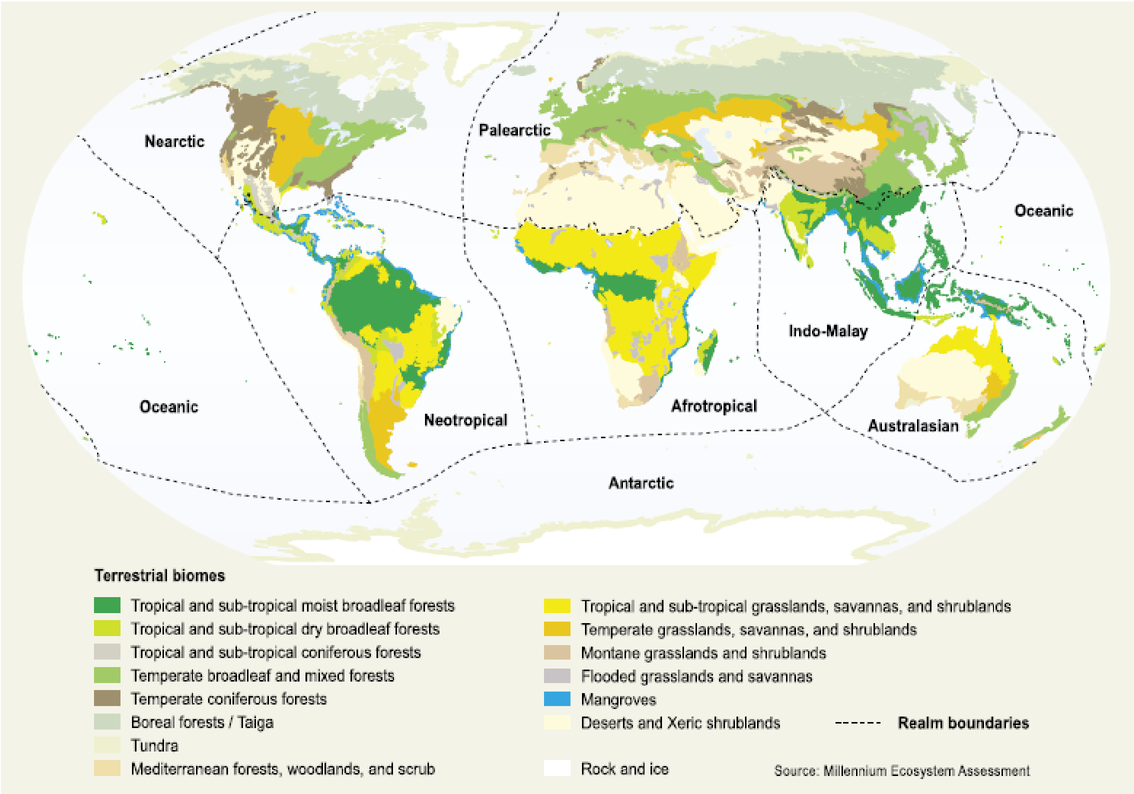

Figure 34 Fourteen biomes of the world. (Millennium Ecosystem Assessment, 2005, p. 24)

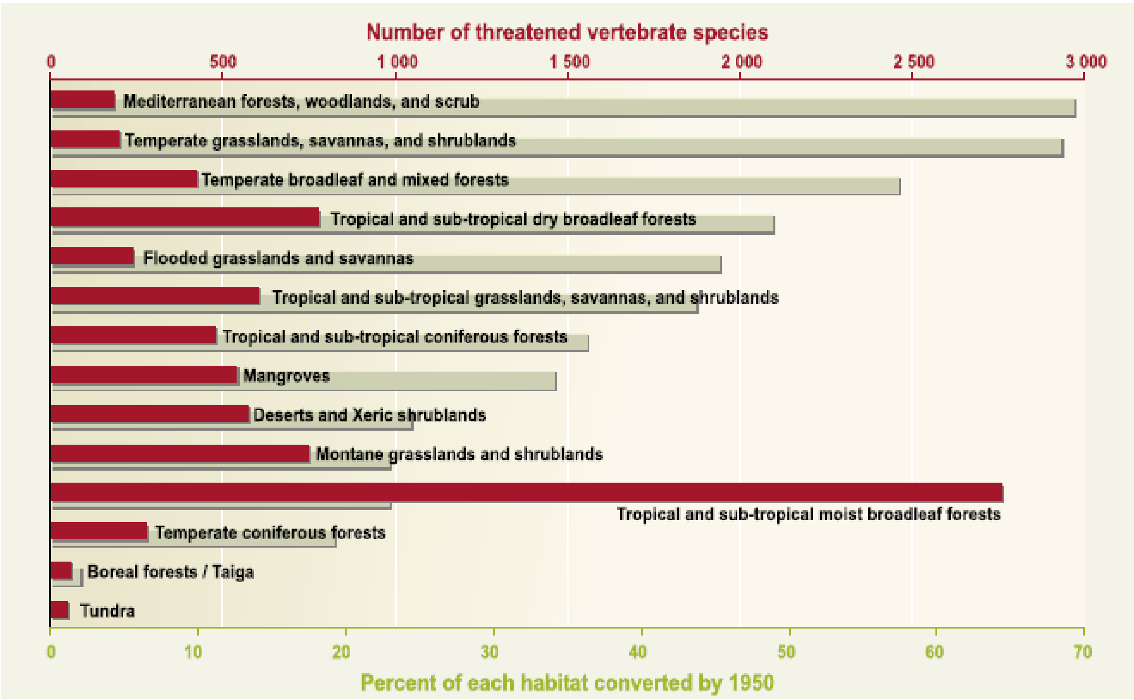

Figure 35 Threatened vertebrates in the 14 biomes, ranked by the amount of their habitat converted by 1950. (Millennium Ecosystem Assessment, 2005, p. 46)

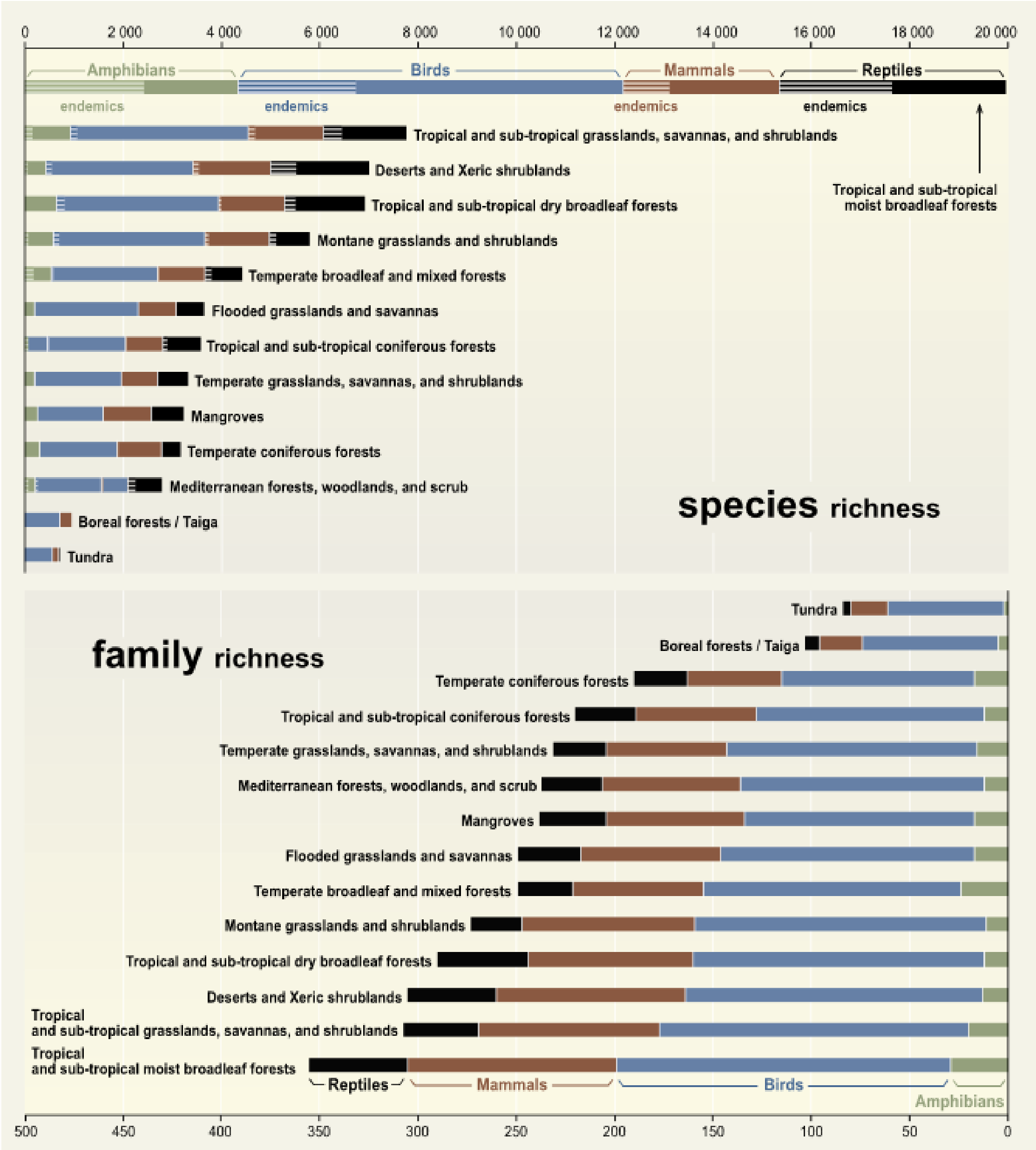

Figure 36 Species richness and family richness of the 14 terrestrial biomes of the world. (Millennium Ecosystem Assessment, 2005, p. 23)

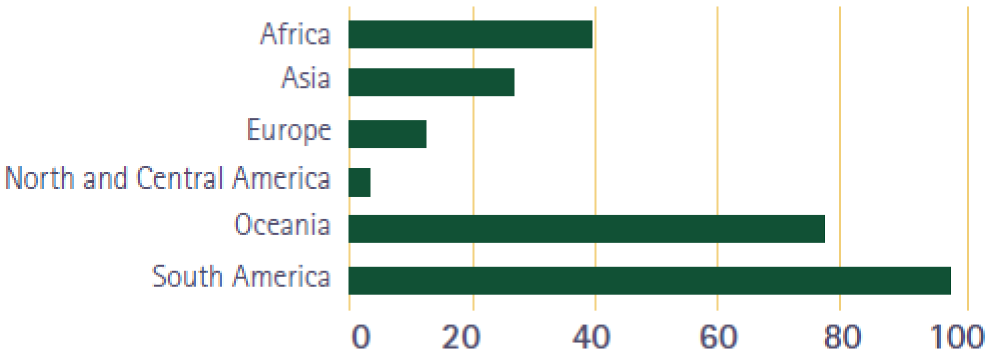

Figure 37 Proportion of planted forests consisting of introduced species, 2010 (%). (FAO, 2010, p. 5)

Species in the forests of South America, Africa, Oceania and Asia still remain the most vulnerable from introduced species. As the most planted forests in those areas have introduced species rather than native species. Refer to Figure 37. With all the above said reasons it can be adequately put that felling trees in Block 2, 3, and 4 countries makes more harm to the ecosystem's biodiversity than felling trees in the Block 1 countries. Hence scores for all the block countries are given as shown in Table 19. CLY since uses wood pulp grown only in tropical forests, it makes the least sustainable, and CV lesser sustainable than CO and PES. PES for natural reasons scores to be the most sustainable in these sustainability indicators.

Table 19 - i15 – Wood harvesting intensity; i16 – Forest area change; i17 – Managed forest area; i18 – Protected forest area as a percent of total forest area; i19 – Threatened species as a percentage of total native species; i20 – Protected area as a percent of total native species.

Fibre production systems	Indicator(s)	Block 1 = 1	Block 2 = 4	Block 3 = 3	Block 4 = 2
CV = 3	$i_{15}, i_{16}, i_{17}, i_{18}, i_{19}, i_{20}$	3	12	9	6
CLY = 4	$i_{15}, i_{16}, i_{17}, i_{18}, i_{19}, i_{20}$	4	16	12	8
CO = 2	$i_{15}, i_{16}, i_{17}, i_{18}, i_{19}, i_{20}$	2	8	6	4
PES = 1	$i_{15}, i_{16}, i_{17}, i_{18}, i_{19}, i_{20}$	1	4	3	2

i_{21} – Emissions of greenhouse gases; i_{22} – Emissions of sulphur oxides; i_{23} – Emissions of nitrogen oxides; i_{24} – Expenditure on air pollution abatement

In the process flow of any fibre production system greenhouse gas emissions essentially occur. As for cotton cultivation, like any other agricultural cultivation, greenhouse gases like methane are emitted from the agricultural fields. In cellulosic production systems like viscose and lyocell processes the greenhouse gases are emitted in the pulping stage, where the degrading of hemicelluloses and other wood matter emits greenhouse gases like carbon dioxide and methane.

Normally the energy consumed by fibre production systems also involves greenhouse gases emissions, since almost all countries produce a significant proportion of their energy from carbon emitting fuels. Especially in Block 2, 3, and 4 countries most of their energy supply comes from carbon emitting fuels. So the sustainability depends more on the nature of energy production for the fibre production system. Integrated pulping and fibre producing facilities are more efficient in usage of energy and they require less energy from the external sources, since burning pulping wastes produces a significant amount of energy which is used for operating the facilities. Cellulosic fibre producing facilities in Block 1 countries are usually integrated facilities.

Sulphur oxides and nitrogen oxides are emitted during pulp producing, and also in fibre producing in the case of viscose fibre production. Pulp production and both cellulosic fibre production systems like viscose and lyocell require caustic soda for processes, and sulphur is an essential ingredient of the viscose spinning solution (cellulose xanthate). (Shen, Worrell, & Patel, 2010) Table 21 shows comparably the emissions involved in different fibre production systems.

CLY seems to be the most sustainable after CO, since the fibre production systems for CLY are present only in Block 1 countries, and it involves no sulphur chemical input and no harmful effluents. PES does better than CV since it doesn't involve as much sulphur chemicals as CV uses. Block 1 countries do the best by reducing emissions from power production and air pollution, followed by Block 3. Block 2 countries do the worst since they get increasingly industrialized and clean power production is of lesser concern than their economy.

Table 20 - i21 – Emissions of greenhouse gases; i22 – Emissions of sulphur oxides; i23 – Emissions of nitrogen oxides, i24 – Expenditure on air pollution abatement;

Fibre production systems	Indicator(s)	Block 1 = 1	Block 2 = 4	Block 3 = 2	Block 4 = 3
CV = 4	i_{21}, i_{22}, i_{23}, i_{24}	4	16	8	12
CLY = 2	i_{21}, i_{22}, i_{23}, i_{24}	2	8	4	6
CO = 1	i_{21}, i_{22}, i_{23}, i_{24}	1	4	2	3
PES = 3	i_{21}, i_{22}, i_{23}, i_{24}	3	12	6	9

i_{26} – Chemically induced acute poisonings; i_{27} – Area of land contaminated with hazardous wastes

Fertilizers used in our case concerns only cotton cultivation, since the use of fertilizers in Eucalyptus plantations is less significant. It has been estimated that the 50-70% of the total nitrogen and phosphorus contaminated in the surface and ground water is caused by fertilizer application. Nitrogen is miscible with water and hence moves with water, and phosphorus get into the sediments of the water bodies and causes eutrophication problems like algal growth and oxygen depletion. (Kooistra & Termorshuizen, 2006, p. 10)

Land contamination and acute poisonings by the use of pesticides have already been discussed in i_8 – Use of agricultural pesticides; i_9 – Use of fertilizers. The other ecological degradation problems induced by different fibre production systems are listed in Table 21. The information given for viscose production system according to the area it's been produced. Refer to Table 22.

Table 21 - Environmental impact of assessment of different fibre production systems from cradele to factory gate. (Shen, Worrell, & Patel, 2010, p. 269)

Fibre production system	**CV (Asia)**	**CV (Austria)**	**CLY**	**CO**	**PES**
Abiotic depletion (kg Sb eq./t)	40	14	20	17	45
Ozone layer depletion ($\times 10^{-4}$ kg CFC11eq./t)	2.8	0.3	1.1	2.0	0.7
Human toxicity (kg 1,4DB eq./t)	1,490	630	470	1,700	4,393
Fresh water aquatic eco-toxicity (kg 1,4DB eq./t)	160	74	85	17,310	58
Terrestrial eco-toxicity (kg 1,4DB eq./t)	16	11	5.0	1,568	12
Photochemical oxidant formation (kg C_2H_4 eq./t)	1.8	0.5	0.6	0.7	1.0
Acidification (kg SO_2 eq./t)	45	14	17	41	21
Eutrophication (kg PO_4^{3-} eq./t)	2.3	1.2	1.8	22	1.2

Considering Table 21, CLY seems to be the most sustainable; followed by CV, PES and CO. Block countries are similarly sustainable as explained in Table 20 for similar reasons.

Table 22 - i26 – Chemically induced acute poisonings; i27 – Area of land contaminated with hazardous wastes

Fibre production systems	**Indicator(s)**	**Block 1 = 1**	**Block 2 = 4**	**Block 3 = 2**	**Block 4 = 3**
CV = 2	i_{26}, i_{27}	2	8	4	6
CLY = 1	i_{26}, i_{27}	1	4	2	3
CO = 4	i_{26}, i_{27}	4	16	8	12
PES = 3	i_{26}, i_{27}	3	12	6	9

i_{28} – Unemployment rate; i_{29} – Head count index of poverty; i_{32} – Women per 100 men in the labour force

The International Labour Organisation has estimated that about 65.1% of the world’s population participates in the labour force of which about 190.2 million people in the world are unemployed. The index, women per 100 men in the labour force, is still under 68. Workers earning less than 2 USD a day have a share of about 80% in Block 4 dominated sub-Saharan and South Asian countries. Women experience considerably high unemployment rate in regions like North Africa, Middle East and Latin America, when compared with unemployment rate of men in those countries. (ILO, 2009)

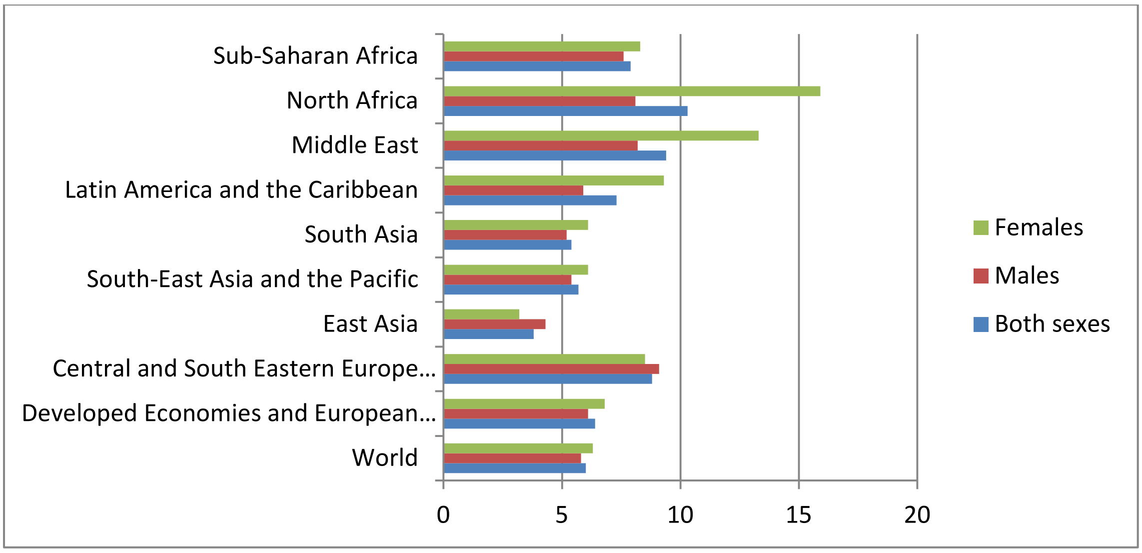

Figure 38 Rate of unemployment in different regions of world as on 2008 (%). (ILO, 2009, p. 30)

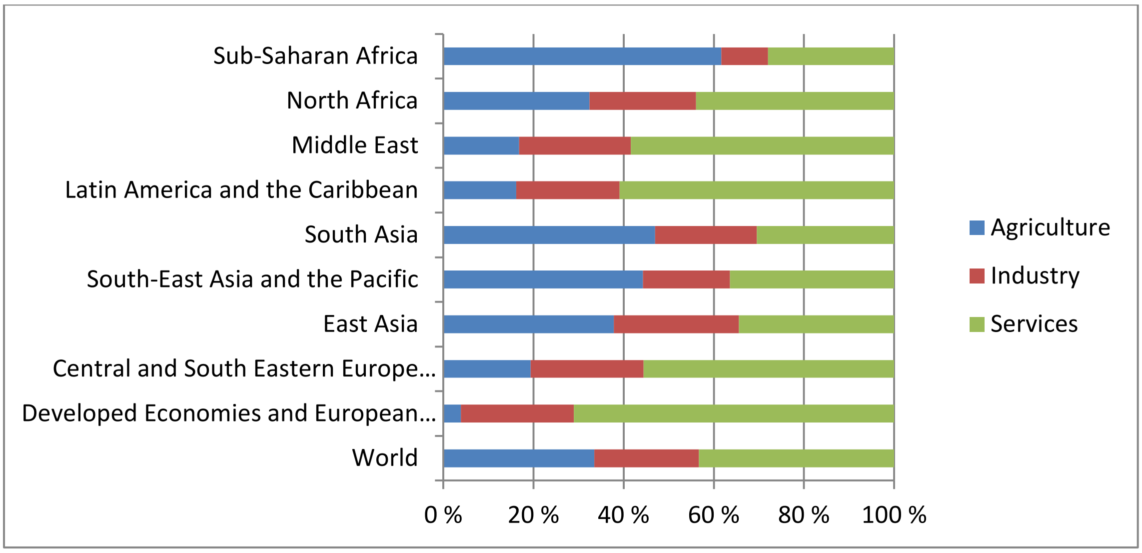

Figure 39 Distribution of employment between different sectors as on 2008 (%). (ILO, 2009, p. 31)

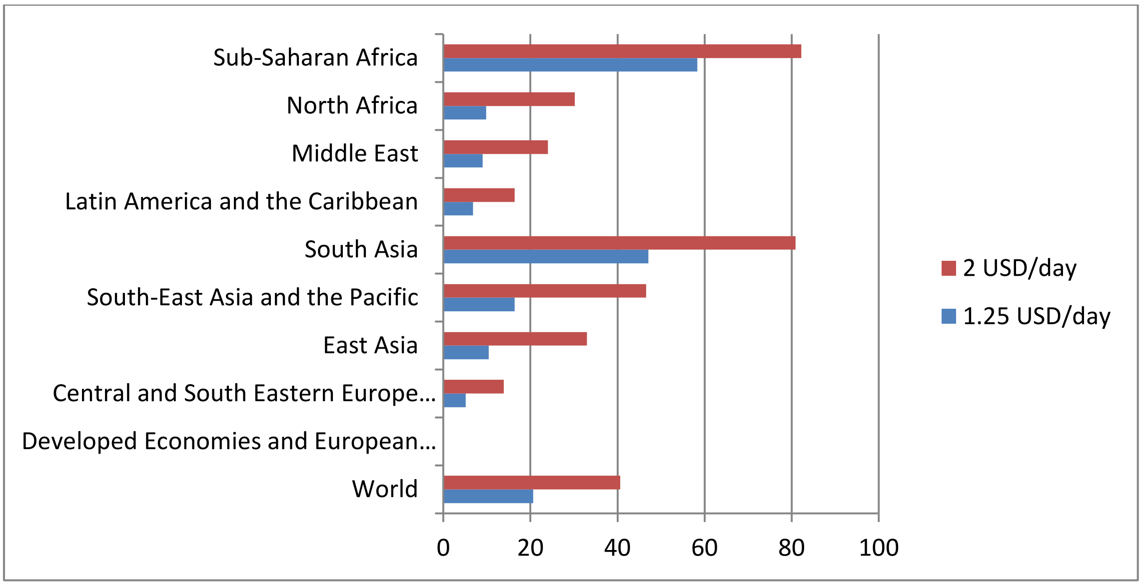

Figure 40 Working poor's share in total employment as on 2007 (%). (ILO, 2009, p. 32)

Cotton fibre production system provides more employment than any other fibre production systems. All the fibre production process of cotton is labour intensive when compared to that of man-made fibres. Women constitute a larger proportion of the working force in cotton cultivation. And also the textile production processes following the fibre production like garment making are labour intensive with mostly women in the work force. So when considering the employment scenario as explained before and also in Figure 38, Figure 39, and Figure 40. Cotton fibre production in Block 4, 2, and 3 are increasingly more sustainable.

Agriculture has the highest employed population in the whole of Asia and sub-Saharan Africa. Industries contribute lesser to employment in all these developing and less developed countries when compared to agriculture. So enhancing agriculture in Block 4, 2, and 3 countries is more sustainable than to develop industries. Block 1 countries apply the most mechanized processes, and thereby employing the least labour force in any fibre production system. Hence Block 4 scores 1 and followed by increasingly industrialised Block countries.

The most sustainable scenario in this indicator's perspective is to develop cotton fibre production systems in Block 4 countries followed by Block 2 and Block 3, since cotton fibre production employs most of the work force. Hence CO scores 1. The least sustainable fibre production system in this indicator's perspective is Polyester in a Block 1 country, since that would employ the least amount of employees. CLY is lesser sustainable than CV because CLY is produced only in Block 1 countries though the raw materials are sourced from other Block countries.

Table 23 - i28 – Unemployment rate; i29 – Head count index of poverty; i32 – Women per 100 men in the labour force

Fibre production systems	Indicator(s)	Block 1 = 4	Block 2 = 2	Block 3 = 3	Block 4 = 1
CV = 2	i_{28}, i_{29}, i_{32}	12	6	9	3
CLY = 3	i_{28}, i_{29}, i_{32}	8	4	6	2
CO = 1	i_{28}, i_{29}, i_{32}	4	2	3	1
PES = 4	i_{28}, i_{29}, i_{32}	16	8	12	4

i_{30} – Population growth rate; i_{31} – Population density

This work classifies the countries of the world into four country blocks. Block 2 countries are the countries with high population growth rate and high population density and fewer resources like India and China. Block 3 and 4 are countries of comparatively moderate population density and have fewer resources per capita. Block 1 countries are developed, less densely populated, and have more resources per capita. On the whole

Block 2, 4, and 3 countries have fewer resources, like water, land, and food, for consumption of its population. And so it is less sustainable to have high resources consuming fibre production systems like cotton, viscose, lyocell, and polyester are decreasingly sustainable respectively. Refer to Figure 41 and Table 24.

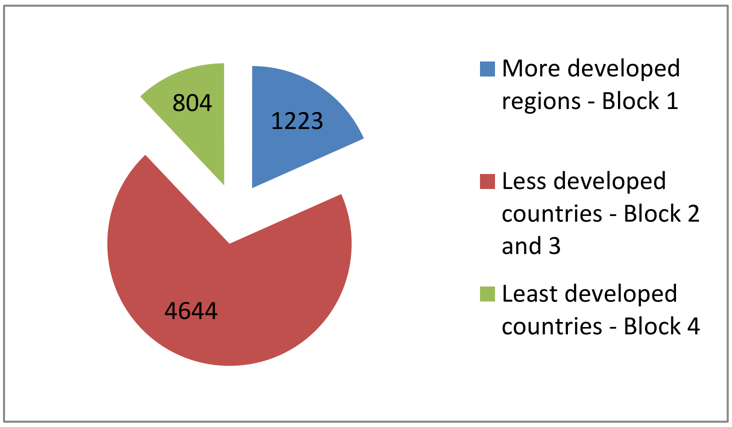

Figure 41 Distribution of population among different country blocks (according to this work) as on 2007 (millions). (UN, 2007)

Table 24 - Population in different continents of the world as on 2007 (millions). (UN, 2007)

Regions of the world	Population in 2007 (millions)
Africa	965
Asia	4030
Europe	731
Latin America and the Caribbean	572
Northern America	339
Oceania	34

i_{34} – Infrastructure expenditure per capita, i_{35} – Net investment share in GDP; i_{37} – Share of manufactured goods in total merchandise exports; i_{39} – Share of manufacturing value added in GDP

i_{34}-i_{42} indicators of sustainability are the economic and institutional sustainability indicators that can possibly be applied for a fibre production system. Most of these indicators are still under development by the UN and the information and data sources for assessing these indicators are not adequately available.

i_{34} – Infrastructure expenditure per capita is the amount of money spent for infrastructure development per person. Larger the spending better is the infrastructure and more sustainable it is on a perspective of a fibre production system. i_{35} – Net investment share indicates the net share of investment in total production, and is measured by dividing gross production capital formation by gross domestic product. i_{37} – Share of manufactured goods in total merchandise exports shows the amount of products being manufactured, in another sense value added, in the country it is coming from. It is less sustainable if the products are just traded or exported without being added any value from the country it is exported from. i_{39} – Share of manufacturing value added in GDP also is similar i_{37} but it is measured by deducting the manufactured goods value from GDP rather than from total merchandise exports as like i_{37}.

All these indicators discussed show the demographical conduciveness of a Block country for hosting a fibre production system. The scores show the same for a Block country and for a fibre production system the scores shows the suitability for all the block countries in the view of sustainability. In that way the scores are given as shown in Table 25.

Table 25 - i30 – Population growth rate; i31 – Population density; i34 – Infrastructure expenditure per capita, i35 – Net investment share in GDP; i37 – Share of manufactured goods in total merchandise exports; i39 – Share of manufacturing value added in GDP

Fibre production systems	Indicator(s)	Block 1 = 1	Block 2 = 3	Block 3 = 2	Block 4 = 4
CV = 2	$i_{30}, i_{31}, i_{34}, i_{35}, i_{37}, i_{39}$	3	12	6	9
CLY = 3	$i_{30}, i_{31}, i_{34}, i_{35}, i_{37}, i_{39}$	2	8	4	6
CO = 4	$i_{30}, i_{31}, i_{34}, i_{35}, i_{37}, i_{39}$	4	16	8	12
PES = 1	$i_{30}, i_{31}, i_{34}, i_{35}, i_{37}, i_{39}$	1	4	2	3

i_{36} – Environmentally adjusted net domestic product; i_{38} – Share of natural resource intensive industries in manufacturing value added; i_{41} – Environmental protection expenditure as a percent of GDP

i_{38} – Share of natural resource intensive industries like viscose and lyocell in manufacturing value added for a country indicates the amount of its economy generated by exploiting its natural resource, which is less sustainable. i_{36} – Environmentally adjusted net domestic product is the net domestic product (NDP) obtained after deducting the environmental costs, and i_{41} – Environmental protection expenditure as a percent of GDP are similarly affected by the environmental cost. Fewer the environmental cost safer is the environment and also larger is the NDP.

i_{40} – Share of consumption of renewable energy resources; i_{42} – Mandated environmental impact assessment;

i_{40} – is the share of consumption of renewable energy resources like biofuels and other. Cellulosic fibre production systems generated biofuels in the pulping process, which can be used for producing renewable energy. And Block 1 countries have high percentage of renewable energy in their total energy consumption. Hence a cellulosic fibre production system is the most sustainable in the perspective this sustainability indicator. i_{42} – Mandated environmental impact assessment is formation of legally binding requirements of a public body at national level for the environmental impact assessment of the fibre production systems. Mandated environmental impact assessment is well practiced in Block 1 countries followed by block 2, 3, and 4 countries.

Table 26 - i36 – Environmentally adjusted net domestic product; i38 – Share of natural resource intensive industries in manufacturing value added; i40 – Share of consumption of renewable energy resources; i41 – Environmental protection expenditure as a percent of GDP; i42 – Mandated environmental impact assessment

Fibre production systems	Indicator(s)	Block 1 = 1	Block 2 = 3	Block 3 = 2	Block 4 = 4
CV = 3	i_{36}, i_{38}, i_{40}, i_{41}, i_{42}	3	9	6	12
CLY = 2	i_{36}, i_{38}, i_{40}, i_{41}, i_{42}	2	6	4	8
CO = 4	i_{36}, i_{38}, i_{40}, i_{41}, i_{42}	4	12	8	16
PES = 1	i_{36}, i_{38}, i_{40}, i_{41}, i_{42}	1	3	2	4

These above five discussed indicators show how much the environment is monitored and protected. Block 1 countries would score the best and block 4 countries would score the worst in all these regards. Also a reason for Block 2 and 4 countries to score 3 and 4 respectively is that they have a bigger share of natural resource intensive industries in their value added manufacturing. PES is scored 1 since it is easier to control and monitor the environmental effects caused by its production systems. CLY is scored 2, for the reason it is only present in Block 1 countries and are monitored very well. CLY, CV, and CO are scored after PES since they have a bigger environmental impact than PES. CO needs the most from environmental monitoring and protection and hence it is scored the least.

6. RESULTS AND DISCUSSIONS

The assessed sustainability indicators for all the fibre production systems with respect to country blocks have been tabulated in the framework tables - Table 31, Table 32, Table 33 and Table 34 in Annex 3. The applied sustainability indicators were totally 42 out of the 96 sustainability indicators as produced by the UNCSD. Average scores of all the applied 42 sustainability indicators for fibre production systems are CV = 2.81, CLY = 2.48, CO = 3.21, and PES = 1.5. Refer to Table 27. These scores show that generally polyester fibre (PES) production system is the most sustainable around the world. After polyester, lyocell scores to be the most sustainable fibre production system, followed by viscose and cotton. Cotton has the most unsustainable fibre production system.

Table 27 - Tabulated relative sustainability indicators

Fibre production systems	Indicators	Block 1 (average score = 1.57)	Block 2 (average score = 3.48)	Block 3 (average score = 2.26)	Block 4 (average score = 2.69)
CV (average score = 2.81)	i_1-i_{42}	4.24	9.9	6.36	7.59
CLY (average score = 2.48)	i_1-i_{42}	3.9	8.62	5.81	6.43
CO (average score = 3.21)	i_1-i_{42}	4.86	11.19	6.98	9.12
PES (average score = 1.5)	i_1-i_{42}	2.71	5.04	3.48	3.48

The average scores given to different block countries are Block 1 = 1.57, Block 2 = 3.48, Block 3 = 2.26, and Block 4 = 2.69. These scores are produced by summing all the scores given to the respective block countries for all the 42 indicators; doing so, four values will be generated each corresponding to a specific fibre production system, which is shown in the previous sentence. Block 1 countries have the most sustainable conditions for hosting a fibre production system, followed by Block 4, Block 3, and Block 2 countries. This means it is more sustainable to have a fibre production system in a Block 4 country than a Block 2 country. The main point of difference is that Block 2 countries don’t have enough natural resources per capita when compared to Block 4 for supporting fibre production systems.

Considering the current trends in fibre market share at polyester (synthetics) having 60%, cotton having around 30%, and cellulosics having around 4-5% (out of which it is mostly viscose and very less lyocell), a radical change in the market shares is expected sooner or later. Though polyester seems to have the most sustainable fibre production system, the raw material scarcity and price increase that is expected in the future will eventually reduce its market share.

If this sustainability assessment could be used for predicting the future fibre market shares, then lyocell and viscose will dominate the future fibre supply followed by polyester and cotton. Such an increase in lyocell and viscose market shares will have to have time to establish the fibre production systems around the world. During the time polyester and other synthetics will be able supply the market adequately, but cotton's share will still remain to be affected. It also makes importance to mention the time when polyester and cotton will start to reduce in shares. For cotton it seems the time has already passed, cotton is experiencing a slump in production and will continue to do so. Polyester currently feeding the slump of cotton production has already grown in price and the increase will be aggravated after 2014 onwards, when the crude oil production rate would get reduced. So cellulosics will find a greater need and demand in a few years to come. And if this happens the cellulosics would achieve highest market share around the year 2050.

The relative sustainability indicators by columns and rows, as shown in Table 27, show the overall sustainability of individual fibre production systems in block countries. The relative sustainability index which ranks all the relative sustainability indicators is produced in the Table 28.

Polyester fibre production systems in Block 1, 3, and 4 countries are respectively the most sustainable, carrying the values 1, 2, and 2 in the relative sustainability index. Block 3 and 4 countries have the same Relative sustainability indicator value for PES. Cotton and viscose fibre production systems in Block 2 countries are the most unsustainable fibre production systems, carrying the values 16 and 15 respectively in the relative sustainability index. Comparing the average relative sustainability indicator values of all the fibres in all the block countries, CO seems to be the most unsustainable and PES seems to be the most sustainable. CLY is more sustainable than CV, even though it uses wood grown only in tropical forests.

Cotton fibre production systems though currently been dominated in the Block 2 countries like China, India and Pakistan is way less sustainable compared to other fibre production systems. Dramatic changes are to be expected with time in cotton production in Block 2 countries, and the changes would move the production of CO to other Block countries. Viscose fibre production systems in Block 2, 3, and 4 countries should be upgraded to standards of those in Block 1 countries in order to make it more sustainable.

Table 28 - Relative sustainability index

Relative sustainability index	Fibre production system-Block	Relative sustainability indicators
1	PES in Block 1	2.71
2	PES in Block 3	3.48
2	PES in Block 4	3.48
4	CLY in Block 1	3.9
5	CV in Block 1	4.24
6	CO in Block 1	4.86
7	PES in Block 2	5.04
8	CLY in Block 3	5.81
9	CV in Block 3	6.36
10	CLY in Block 4	6.43
11	CO in Block 3	6.98
12	CV in Block 4	7.59
13	CLY in Block 2	8.62
14	CO in Block 4	9.12
15	CV in Block 2	9.9
16	CO in Block 2	11.19

Referring to the distribution of the scores among different applied sustainability indicators, CLY scores better than CV in most of the indicators except with forestry based indicators. CLY fibre production system in Block 2, 3 and 4 countries are given values even though there are no production sites in those countries; however these values hold good if a production site of CLY would be established in these respective countries. Though CLY is already more sustainable than CV, its sustainability could be improved substantially by using wood pulp produced in temperate forests, provided the production of CLY stays in Block 1 countries. Or else a new cellulose fibre production system like CCA in Block 1 would be commercialised and uses temperate dissolving pulps, can potentially be the most sustainable.

Fibre production systems in Block 1 countries, owing to its high sustainable production systems, will experience very low dynamics in the future. If it does it will be an increase in capacity and production. Production systems especially like lyocell and viscose processes will continue to do better when compared to other fibre production systems all over the world. Cellulosic fibres from Block 1 would continue to dominate the fibre market if the price competitiveness of cellulosic fibres from Block 2, 3, and 4 are overcome.

7. CONCLUSIONS

Some recommendations for more sustainable textile supply chain:

- Lyocell process should be upgraded to use wood from temperate forests. Reduced amounts of wood to be used from tropical forests.
- New pulp dissolving methods like Cel-Sol and fibre making methods like CCA processes, which are more environmentally friendly and sustainable should be encouraged.
- Lyocell process should be more established and increased in capacity.
- Modified viscose processes using lesser chemicals and with better chemical recovery should be developed.
- Research and development of viscose and other cellulosic fibres should be encouraged.
- Functionality of different cellulosic fibres should be increased by cellulose functionalization.
- New eco-friendly cellulose solvents like ionic liquids should be developed.
- Cellulosics production in Block 1 countries should be encouraged and increased in capacity.
- Cotton fibre production in Block 2 countries should be shifted to Block 1 or Block 4 countries.
- Cotton production should be carried out in areas where water availability is adequate, and doesn't take water from the population's own use.
- Pesticide and fertilizers use to be reduced. Organic cotton should be encouraged.
- Post fibre textile production for Block 1 countries should be carried in Block 3 countries, with the fibres sourced from Block 1 countries.
- Only labour intensive textile manufacturing processes like garment making should be encouraged in Block 2.

This work tried to give a holistic view on sustainability of fibre production systems around the world. Similar studies on individual countries of the world and various fibre production systems are recommendable.

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9. ANNEXURE

Annex 1

Table 29 - Working list of indicators of sustainable development, as given by the UN in the Methodology Sheets (UN, 2007)

NO	INDICATORS
1	PROPORTION OF POPULATION LIVING BELOW NATIONAL POVERTY LINE
2	PROPORTION OF POPULATION BELOW 1 $ A DAY
3	RATIO OF SHARE IN NATIONAL INCOME OF HIGHEST TO LOWEST QUINTILE
4	PROPORTION OF POPULATION USING IMPROVED SANITATION FACILITIES
5	PROPORTION OF POPULATION USING AN IMPROVED WATER SOURCE
6	SHARE OF HOUSEHOLDS WITHOUT ELECTRICITY OR OTHER MODERN ENERGY SERVICES
7	PERCENTAGE OF POPULATION USING SOLID FUELS FOR COOKING
8	PROPORTION OF URBAN POPULATION LIVING IN SLUMS
9	PERCENTAGE OF POPULATION HAVING PAID BRIBES
10	NUMBER OF INTENTIONAL HOMICIDES PER 100,000 POPULATION
11	UNDER-FIVE MORTALITY RATE
12	LIFE EXPECTANCY AT BIRTH
13	HEALTHY LIFE EXPECTANCY AT BIRTH
14	PERCENT OF POPULATION WITH ACCESS TO PRIMARY HEALTH CARE FACILITIES
15	CONTRACEPTIVE PREVALENCE RATE
16	IMMUNIZATION AGAINST INFECTIOUS CHILDHOOD DISEASES
17	NUTRITIONAL STATUS OF CHILDREN
18	MORBIDITY OF MAJOR DISEASES SUCH AS HIV/AIDS, MALARIA, TUBERCULOSIS
19	PREVALENCE OF TOBACCO USE
20	SUICIDE RATE
21	GROSS INTAKE RATIO TO LAST GRADE OF PRIMARY EDUCATION
22	NET ENROLMENT RATE IN PRIMARY EDUCATION
23	ADULT SECONDARY (TERTIARY) SCHOOLING ATTAINMENT LEVEL
24	LIFE-LONG LEARNING
25	ADULT LITERACY RATE
26	POPULATION GROWTH RATE
27	TOTAL FERTILITY RATE
28	DEPENDENCY RATIO
29	RATIO OF LOCAL RESIDENTS TO TOURISTS IN MAJOR TOURIST REGIONS AND DESTINATIONS

30	PERCENTAGE OF POPULATION LIVING IN HAZARD PRONE AREAS
31	HUMAN AND ECONOMIC LOSS DUE TO DISASTERS
32	CARBON DIOXIDE EMISSIONS
33	EMISSIONS OF GREENHOUSE GASES
34	CONSUMPTION OF OZONE DEPLETING SUBSTANCES
35	AMBIENT CONCENTRATION OF AIR POLLUTANTS IN URBAN AREAS
36	LAND USE CHANGE
37	LAND DEGRADATION
38	LAND AFFECTED BY DESERTIFICATION
39	ARABLE AND PERMANENT CROPLAND AREA
40	FERTILIZER USE EFFICIENCY
41	USE OF AGRICULTURAL PESTICIDES
42	AREA UNDER ORGANIC FARMING
43	PROPORTION OF LAND AREA COVERED BY FORESTS
44	AREA OF FOREST UNDER SUSTAINABLE FOREST MANAGEMENT
45	PERCENT OF FOREST TREES DAMAGED BY DEFOLIATION
46	PERCENTAGE OF TOTAL POPULATION LIVING IN COASTAL AREAS
47	BATHING WATER QUALITY
48	PROPORTION OF FISH STOCKS WITHIN THEIR SAFE BIOLOGICAL LIMITS
49	PROPORTION OF MARINE AREAS PROTECTED
50	MARINE TROPHIC INDEX
51	AREA OF CORAL REEF ECOSYSTEMS AND PERCENTAGE LIVE COVER
52	PROPORTION OF TOTAL WATER RESOURCES USED
53	WATER USE INTENSITY BY ECONOMIC ACTIVITY
54	PRESENCE OF FAECAL COLIFORMS IN FRESHWATER
55	BIOCHEMICAL OXYGEN DEMAND IN WATER BODIES
56	WASTEWATER TREATMENT
57	PROPORTION OF TERRESTRIAL AREA PROTECTED, TOTAL AND BY ECO-LOGICAL REGION
58	MANAGEMENT EFFECTIVENESS OF PROTECTED AREAS
59	AREA OF SELECTED KEY ECOSYSTEMS
60	FRAGMENTATION OF HABITATS
61	CHANGE IN THREAT STATUS OF SPECIES
62	ABUNDANCE OF SELECTED KEY SPECIES
63	ABUNDANCE OF INVASIVE ALIEN SPECIES
64	GROSS DOMESTIC PRODUCT PER CAPITA
65	INVESTMENT SHARE IN GROSS DOMESTIC PRODUCT
66	GROSS SAVING
67	ADJUSTED NET SAVING AS A PERCENTAGE OF GROSS NATIONAL INCOME
68	INFLATION RATE
69	DEBT-TO-GNI RATIO
70	EMPLOYMENT-TO-POPULATION RATIO
71	VULNERABLE EMPLOYMENT
72	LABOUR PRODUCTIVITY AND UNIT LABOUR COST

73	SHARE OF WOMEN IN WAGE EMPLOYMENT IN NON-AGRICULTURAL SECTOR
74	INTERNET USERS PER 100 POPULATION
75	FIXED TELEPHONE LINES PER 100 POPULATION
76	MOBILE CELLULAR TELEPHONE SUBSCRIBERS PER 100 POPULATION
77	GROSS DOMESTIC EXPENDITURE ON RESEARCH AND DEVELOPMENT AS A PERCENT OF GROSS DOMESTIC PRODUCT
78	TOURISM CONTRIBUTION TO GDP
79	CURRENT ACCOUNT DEFICIT AS PERCENTAGE OF GDP
80	SHARE OF IMPORTS FROM DEVELOPING COUNTRIES AND LDCS
81	AVERAGE TARIFF IMPOSED ON EXPORTS FROM DEVELOPING COUNTRIES AND LDCS
82	NET OFFICIAL DEVELOPMENT ASSISTANCE GIVEN OR RECEIVED AS A PERCENTAGE OF GROSS NATIONAL INCOME
83	REMITTANCES AS PERCENTAGE OF GNI
84	FOREIGN DIRECT INVESTMENT (FDI) NET INFLOWS AND NET OUTFLOWS AS SHARE OF GDP
85	MATERIAL INTENSITY OF THE ECONOMY
86	DOMESTIC MATERIAL CONSUMPTION
87	ANNUAL ENERGY CONSUMPTION, TOTAL AND BY MAIN USER CATEGORY
88	INTENSITY OF ENERGY USE, TOTAL AND BY ECONOMIC ACTIVITY
89	SHARE OF RENEWABLE ENERGY SOURCES IN TOTAL ENERGY USE
90	GENERATION OF HAZARDOUS WASTES
91	GENERATION OF WASTE
92	WASTE TREATMENT AND DISPOSAL
93	MANAGEMENT OF RADIOACTIVE WASTE
94	MODAL SPLIT OF PASSENGER TRANSPORT
95	MODAL SPLIT OF FREIGHT TRANSPORT
96	ENERGY INTENSITY OF TRANSPORT

Annex 2

Table 30 - List of members of the United Nations as on 28 June 2006, clustered into blocks as used in this work. (Press Release of the UN on UN Member States, 2006) (Nordås, 2004)

No.	Block 1	Block 2	Block 3	Block 4	
1	Australia	Argentina	Bahamas	Afganistan	Marshall Islands
2	Austria	Bangladesh	Belarus[1]	Albania	Mauritania
3	Bahrain	Brazil	Bosnia and Herzegovina[2]	Algeria	Mauritius
4	Belgium	Bhutan	Bulgaria	Andorra	Micronesia (Federated States of)
5	Brunei Darussalam	Chile	Barbados	Angola	Mongolia
6	Canada	China	Costa Rica	Antigua and Barbuda	Montenegro[10]
7	Czech Republic[4]	Cuba	Croatia[3]	Armenia	Mozambique
8	Denmark	Egypt[6]	Cyprus	Azerbaijan	Myanmar
9	Finland	Gabon	Dominica	Belize	Namibia
10	France	Greece	Dominican Republic	Benin	Nauru
11	Germany[7]	Guatemala	Ecuador	Bolivia	Nicaragua
12	Iceland	Colombia	Estonia	Botswana	Niger
13	Hungary	India	Georgia	Burkina Faso	Nigeria
14	Ireland	Indonesia[8]	Fiji	Burundi	Palau
15	Italy	Iran	El Salvador	Cambodia	Papua New Guinea
16	Japan	Israel	Eritrea	Cameroon	Paraguay
17	Kuwait	Kazakhstan	Jamaica	Central African Republic	Peru
18	Liechtenstein	Kenya	Jordan	Congo (Republic of the)	Rwanda
19	Luxembourg	Lebanon	Latvia	Cape Verde	Saint Kitts and Nevis
20	Malaysia[9]	Nepal	Lesotho	Chad	Saint Lucia
21	Monaco	Pakistan	Lithuania	Comoros	Saint Vincent and the Grenadines
22	Netherlands	Philippines	Morocco	Côte d'Ivoire	Samoa
23	New Zealand	Poland	Panama	Democratic People's Republic of Korea	San Marino
24	Norway	Portugal	Republic of Moldova	Democratic Republic of	Sao Tome and Principe

				the Congo[5]	
25	Oman	South Africa	Romania	Djibouti	Senegal
26	Qatar	Slovakia[13]	Serbia[12]	Equatorial Guinea	Seychelles
27	Republic of Korea	Sri Lanka	Slovenia[14]	Ethiopia	Sierra Leone
28	Russian Federation[11]	Tajikistan	Tunisia	Gambia	Solomon Islands
29	Saudi Arabia	Thailand	Ukraine	Ghana	Somalia
30	Singapore	Turkey	Mexico	Grenada	Sudan
31	Spain	Turkmenistan		Haiti	Suriname
32	Switzerland	Uzbekistan		Honduras	Swaziland
33	Sweden	Venezuela		Iraq	Syria[15]
34	United Arab Emirates	Viet Nam		Kyrgyzstan	The former Yugoslav Republic of Macedonia[16]
35	United Kingdom			Libya	Timor Leste
36	United States			Madagascar	Togo
37				Maldives	Tonga
38				Guinea	Trinidad and Tobago
39				Guinea-Bissau	Tuvalu
40				Guyana	Uganda
41				Kiribati	United of Republic of Tanzania[17]
42				Lao People's Democratic Republic	Uruguay
43				Liberia	Yemen[18]
44				Malawi	Vanuatu
45				Mali	Zambia
46				Malta	Zimbabwe

Annex 3

Table 31 - Sustainability indicators scoring framework for viscose fibre production system.

Fibre production system: CV						
Indicators of sustainability, *i*	i_n	**Score CV**	**Sustainability scores**			
			Block 1	**Block 2**	**Block 3**	**Block 4**
Annual withdrawals of ground and surface water	i_1	3	3	12	6	9
Ground water reserve	i_2	3	3	12	6	9
Wastewater treatment	i_3	3	3	12	6	9
Land use change	i_4	2	8	6	4	2
Changes in land conditions	i_5	2	8	6	4	2
Satellite derived vegetation index	i_6	2	8	6	4	2
Land affected by desertification	i_7	2	8	6	4	2
Use of agricultural pesticides	i_8	2	2	6	4	8
Use of fertilizers	i_9	2	2	6	4	8
Irrigation percent of arable land	i_{10}	2	2	8	4	6
Energy use in agriculture	i_{11}	3	12	9	6	3
Arable land per capita	i_{12}	2	2	4	6	8
Area affected by salinization and water logging	i_{13}	2	2	8	4	6
Agricultural education	i_{14}	2	2	4	6	8
Wood harvesting intensity	i_{15}	3	3	12	9	6
Forest area change	i_{16}	3	3	12	9	6
Managed forest area ratio	i_{17}	3	3	12	9	6
Protected forest area as a percent of total forest area	i_{18}	3	3	12	9	6
Threatened species as a percent of total native species	i_{19}	3	3	12	9	6
Protected area as a percent of total area	i_{20}	3	3	12	9	6
Emissions of greenhouse gases	i_{21}	4	4	16	8	12
Emissions of sulphur oxides	i_{22}	4	4	16	8	12
Emissions of nitrogen oxides	i_{23}	4	4	16	8	12
Expenditure on air pollution abatement	i_{24}	4	4	16	8	12
Expenditure on waste management	i_{25}	3	3	12	6	9
Chemically induced acute poisonings	i_{26}	2	2	8	4	6
Area of land contaminated with hazard-	i_{27}	2	2	8	4	6

ous wastes						
Unemployment rate	i_{28}	3	12	6	9	3
Head count index of poverty	i_{29}	3	12	6	9	3
Population growth rate	i_{30}	3	3	12	6	9
Population density	i_{31}	3	3	12	6	9
Women per 100 men in the labour force	i_{32}	3	12	6	9	3
Access to safe drinking water	i_{33}	3	3	12	6	9
Infrastructure expenditure per capita	i_{34}	3	3	12	6	9
Net investment share in GDP	i_{35}	3	3	12	6	9
Environmentally adjusted net domestic product	i_{36}	3	3	9	6	12
Share of manufactured goods in total merchandise exports	i_{37}	3	3	12	6	9
Share of natural resource intensive industries in manufacturing value added	i_{38}	3	3	9	6	12
Share of manufacturing value added in GDP	i_{39}	3	3	12	6	9
Share of consumption of renewable energy resources	i_{40}	3	3	9	6	12
Environmental protection expenditure as a percent of GDP	i_{41}	3	3	9	6	12
Mandated environmental impact assessment	i_{42}	3	3	9	6	12
Sum of scores, $(\sum 42\_(i = 1)\hat{}n▒S\_i)$			178	416	267	319
Relative sustainability indicators of CV fibre production system			4.238095	9.904762	6.357143	7.595238

Table 32 - Sustainability indicators scoring framework for lyocell fibre production system.

Fibre production system: CLY						
Indicators of sustainability, *i*	i_n	**Score CLY**	**Sustainability scores**			
			Block 1	**Block 2**	**Block 3**	**Block 4**
Annual withdrawals of ground and surface water	i_1	2	2	8	4	6
Ground water reserve	i_2	2	2	8	4	6
Wastewater treatment	i_3	2	2	8	4	6
Land use change	i_4	3	12	9	6	3
Changes in land conditions	i_5	3	12	9	6	3
Satellite derived vegetation index	i_6	3	12	9	6	3
Land affected by desertification	i_7	3	12	9	6	3
Use of agricultural pesticides	i_8	3	3	9	6	12
Use of fertilizers	i_9	3	3	9	6	12
Irrigation percent of arable land	i_{10}	3	3	12	6	9
Energy use in agriculture	i_{11}	2	8	6	4	2
Arable land per capita	i_{12}	3	3	6	9	12
Area affected by salinization and water logging	i_{13}	3	3	12	6	9
Agricultural education	i_{14}	3	3	6	9	12
Wood harvesting intensity	i_{15}	4	4	16	12	8
Forest area change	i_{16}	4	4	16	12	8
Managed forest area ratio	i_{17}	4	4	16	12	8
Protected forest area as a percent of total forest area	i_{18}	4	4	16	12	8
Threatened species as a percent of total native species	i_{19}	4	4	16	12	8
Protected area as a percent of total area	i_{20}	4	4	16	12	8
Emissions of greenhouse gases	i_{21}	2	2	8	4	6
Emissions of sulphur oxides	i_{22}	2	2	8	4	6
Emissions of nitrogen oxides	i_{23}	2	2	8	4	6
Expenditure on air pollution abatement	i_{24}	2	2	8	4	6
Expenditure on waste management	i_{25}	2	2	8	4	6
Chemically induced acute poisonings	i_{26}	1	1	4	2	3
Area of land contaminated with hazardous wastes	i_{27}	1	1	4	2	3

Unemployment rate	i_{28}	2	8	4	6	2
Head count index of poverty	i_{29}	2	8	4	6	2
Population growth rate	i_{30}	2	2	8	4	6
Population density	i_{31}	2	2	8	4	6
Women per 100 men in the labour force	i_{32}	2	8	4	6	2
Access to safe drinking water	i_{33}	2	2	8	4	6
Infrastructure expenditure per capita	i_{34}	2	2	8	4	6
Net investment share in GDP	i_{35}	2	2	8	4	6
Environmentally adjusted net domestic product	i_{36}	2	2	6	4	8
Share of manufactured goods in total merchandise exports	i_{37}	2	2	8	4	6
Share of natural resource intensive industries in manufacturing value added	i_{38}	2	2	6	4	8
Share of manufacturing value added in GDP	i_{39}	2	2	8	4	6
Share of consumption of renewable energy resources	i_{40}	2	2	6	4	8
Environmental protection expenditure as a percent of GDP	i_{41}	2	2	6	4	8
Mandated environmental impact assessment	i_{42}	2	2	6	4	8
Sum of scores, (∑42_(i = 1)^n▒S_i)			164	362	244	270
Relative sustainability indicators of CLY fibre production system			3.904762	8.619048	5.809524	6.428571

Table 33 - Sustainability indicators scoring framework for cotton fibre production system.

Fibre production system: CO						
Indicators of sustainability, *i*	i_n	**Score CO**	**Sustainability scores**			
			Block 1	**Block 2**	**Block 3**	**Block 4**
Annual withdrawals of ground and surface water	i_1	4	4	16	8	12
Ground water reserve	i_2	4	4	16	8	12
Wastewater treatment	i_3	4	4	16	8	12
Land use change	i_4	4	16	12	8	4
Changes in land conditions	i_5	4	16	12	8	4
Satellite derived vegetation index	i_6	4	16	12	8	4
Land affected by desertification	i_7	4	16	12	8	4
Use of agricultural pesticides	i_8	4	4	12	8	16
Use of fertilizers	i_9	4	4	12	8	16
Irrigation percent of arable land	i_{10}	4	4	16	8	12
Energy use in agriculture	i_{11}	4	16	12	8	4
Arable land per capita	i_{12}	4	4	8	12	16
Area affected by salinization and water logging	i_{13}	4	4	16	8	12
Agricultural education	i_{14}	4	4	8	12	16
Wood harvesting intensity	i_{15}	2	2	8	6	4
Forest area change	i_{16}	2	2	8	6	4
Managed forest area ratio	i_{17}	2	2	8	6	4
Protected forest area as a percent of total forest area	i_{18}	2	2	8	6	4
Threatened species as a percent of total native species	i_{19}	2	2	8	6	4
Protected area as a percent of total area	i_{20}	2	2	8	6	4
Emissions of greenhouse gases	i_{21}	1	1	4	2	3
Emissions of sulphur oxides	i_{22}	1	1	4	2	3
Emissions of nitrogen oxides	i_{23}	1	1	4	2	3
Expenditure on air pollution abatement	i_{24}	1	1	4	2	3
Expenditure on waste management	i_{25}	4	4	16	8	12
Chemically induced acute poisonings	i_{26}	4	4	16	8	12
Area of land contaminated with hazardous wastes	i_{27}	4	4	16	8	12

Unemployment rate	i_{28}	1	4	2	3	1
Head count index of poverty	i_{29}	1	4	2	3	1
Population growth rate	i_{30}	4	4	16	8	12
Population density	i_{31}	4	4	16	8	12
Women per 100 men in the labour force	i_{32}	1	4	2	3	1
Access to safe drinking water	i_{33}	4	4	16	8	12
Infrastructure expenditure per capita	i_{34}	4	4	16	8	12
Net investment share in GDP	i_{35}	4	4	16	8	12
Environmentally adjusted net domestic product	i_{36}	4	4	12	8	16
Share of manufactured goods in total merchandise exports	i_{37}	4	4	16	8	12
Share of natural resource intensive industries in manufacturing value added	i_{38}	4	4	12	8	16
Share of manufacturing value added in GDP	i_{39}	4	4	16	8	12
Share of consumption of renewable energy resources	i_{40}	4	4	12	8	16
Environmental protection expenditure as a percent of GDP	i_{41}	4	4	12	8	16
Mandated environmental impact assessment	i_{42}	4	4	12	8	16
Sum of scores, $\left(\sum_{i=1}^{n} S_i\right)$			204	470	293	383
Relative sustainability indicators of CO fibre production system			4.857143	11.19048	6.97619	9.119048

Table 34 - Sustainability indicators scoring framework for polyester fibre production system.

Fibre production system: PES						
Indicators of sustainability, *i*	i_n	**Score PES**	**Sustainability scores**			
			Block 1	**Block 2**	**Block 3**	**Block 4**
Annual withdrawals of ground and surface water	i_1	1	1	4	2	3
Ground water reserve	i_2	1	1	4	2	3
Wastewater treatment	i_3	1	1	4	2	3
Land use change	i_4	1	4	3	2	1
Changes in land conditions	i_5	1	4	3	2	1
Satellite derived vegetation index	i_6	1	4	3	2	1
Land affected by desertification	i_7	1	4	3	2	1
Use of agricultural pesticides	i_8	1	1	3	2	4
Use of fertilizers	i_9	1	1	3	2	4
Irrigation percent of arable land	i_{10}	1	1	4	2	3
Energy use in agriculture	i_{11}	1	4	3	2	1
Arable land per capita	i_{12}	1	1	2	3	4
Area affected by salinization and water logging	i_{13}	1	1	4	2	3
Agricultural education	i_{14}	1	1	2	3	4
Wood harvesting intensity	i_{15}	1	1	4	3	2
Forest area change	i_{16}	1	1	4	3	2
Managed forest area ratio	i_{17}	1	1	4	3	2
Protected forest area as a percent of total forest area	i_{18}	1	1	4	3	2
Threatened species as a percent of total native species	i_{19}	1	1	4	3	2
Protected area as a percent of total area	i_{20}	1	1	4	3	2
Emissions of greenhouse gases	i_{21}	3	3	12	6	9
Emissions of sulphur oxides	i_{22}	3	3	12	6	9
Emissions of nitrogen oxides	i_{23}	3	3	12	6	9
Expenditure on air pollution abatement	i_{24}	3	3	12	6	9
Expenditure on waste management	i_{25}	1	1	4	2	3
Chemically induced acute poisonings	i_{26}	3	3	12	6	9
Area of land contaminated with hazardous wastes	i_{27}	3	3	12	6	9

Unemployment rate	i_{28}	4	16	8	12	4
Head count index of poverty	i_{29}	4	16	8	12	4
Population growth rate	i_{30}	1	1	4	2	3
Population density	i_{31}	1	1	4	2	3
Women per 100 men in the labour force	i_{32}	4	16	8	12	4
Access to safe drinking water	i_{33}	1	1	4	2	3
Infrastructure expenditure per capita	i_{34}	1	1	4	2	3
Net investment share in GDP	i_{35}	1	1	4	2	3
Environmentally adjusted net domestic product	i_{36}	1	1	3	2	4
Share of manufactured goods in total merchandise exports	i_{37}	1	1	4	2	3
Share of natural resource intensive industries in manufacturing value added	i_{38}	1	1	3	2	4
Share of manufacturing value added in GDP	i_{39}	1	1	4	2	3
Share of consumption of renewable energy resources	i_{40}	1	1	3	2	4
Environmental protection expenditure as a percent of GDP	i_{41}	1	1	3	2	4
Mandated environmental impact assessment	i_{42}	1	1	3	2	4
Sum of scores, (∑42_(i = 1)^n▒S_i)			114	212	146	158
Relative sustainability indicators of PES fibre production system			2.714286	5.047619	3.47619	3.761905

[i] United Nations Framework Convention on Climate Change.
[ii] Conference of Parties, 15th conference.
[iii] Definition officially adopted by the United Nations and originally given by Gro Harlem Bruntland. (1987). Our common future: the World Commission on Environment and Development. Oxford University Press.
[iv] For more information: <http://www.un.org/esa/dsd/dsd_aofw_ind/ind_index.shtml>
[v] Global Competitiveness Report evaluates economic sustainability. (Schwab, Klaus, 2010)
[vi] Environmental Performance Index evaluates environmental sustainability. (Esty, Kim, Srebotnjak, Levy, Sherbinin, & Mara, 2008). http://epi.yale.edu
[vii] Global Reporting Initiative helps in reporting overall sustainability of an institution. http://www.globalreporting.home