Carbon Footprint of Textile and Clothing Products

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7.1 INTRODUCTION

There exists an enormous pressure on the earth to protect its natural environment. Human activities, increase in human needs, and sophistication lead to deterioration of the natural environmental system. Consumption of electricity, food, clothing, etc., is steadily raising, leading to a continuous growth of related industries. So the amount of greenhouse gas (GHG) emission is also continuously increasing. Excessive emission of GHG elicits pollution and worsens the condition of nature.[1]

There are two types of carbon footprints:

1. Primary carbon footprint
2. Secondary carbon footprint

Primary carbon footprint is the result of direct emission of GHG due to combustion of fossil fuels, and this type of carbon footprint is in our direct control. Primary carbon footprint is the outcome of transportation, domestic energy consumption, etc. On the other hand, secondary carbon footprint is the result of indirect emission of GHG during the entire life cycle of different products. This may occur due to use of clothing, recreation and leisure goods, etc.[1,2]

Many organizations have been formed to keep an update and control over the carbon footprint. The following are some of the organizations working internationally to reduce GHG emissions and that developed some of the standards or standard methods to evaluate GHG emissions:

- International Standards Organization (ISO)
- United Nations Framework Convention on Climate Change (UNFCCC)
- Intergovernmental Panel on Climate Change (IPCC)
- World Resources Institute (WRI) and World Business Council for Sustainable Development (WBCSD)
- Organisation for Economic Co-operation and Development (OECD)–International Energy Agency (IEA)
- U.S. Department of Energy (DOE)
- Lawrence Berkeley National Laboratory (LBNL)
- California Climate Change Registry

Some of the agencies such as IEA and U.S. DOE maintain and publish statistics on the energy consumption and emission levels of CO_2 and thereby help to control the emission of GHG by various countries. The former works for ensuring reliable, affordable, and clean energy for its member counties and the rest of the world, and the latter works for the United States. UNFCC was established in 1992 and helps to stabilize the concentration of GHG in the atmosphere at a certain level, preventing dangerous human interface with the climate system. IPCC is a scientific body that gives a clear view on climate change all over the world. Currently, more than 195 countries are members of the IPCC that actively participate in the assessment of climate change. LBNL is associated with and managed by the University of California. It is conducting research on a wide range of topics including environmental assessment and emission of GHGs. California Climate Change Registry collects the verified reports on GHG emission in the region of California and the rest of the regions too. It helps to stabilize the emission of GHGs in the recorded regions of California.

These organizations have developed standards to study the presence of GHGs and quantify GHGs; equivalent factors for GHG; GHG protocol; guidelines for monitoring, evaluation, reporting, verification, and certification of energy-related projects; and saving of water.[3] Even after the effective control of GHG emission, many regions such as Latin America, Asia, and China are still above and continuously increasing than the global average CO_2 emission of 1.3 gigaton in 2009–2010.[4] In this chapter, various aspects, types, and sources of GHG, carbon footprint and its importance, carbon footprint of various textile processes, and natural as well as synthetic fiber products will be discussed in detail.

7.2 GREENHOUSE GASES

GHGs are the basis of assessment of carbon footprint of various processes, products, and entities. The sun produces radiation that reaches the earth mainly in three wavelength regions, namely, ultraviolet, visible, and infrared. These radiations coming to the earth are partly reflected and partly absorbed. The absorbed radiation increases the temperature of the earth and radiates some of the energy. When equilibrium is achieved between absorbed and radiated energy, almost constant average temperature is achieved. Such emitted radiations may not be reflected completely from the earth and may be partially absorbed and trapped by the gases present in troposphere. The absorbed gases are reflected in all directions and some of the radiations are returned back to the earth. This leads to increase in temperature of the earth resulting in global warming. This effect is called as a *greenhouse effect*. The gases responsible for this effect are GHGs.

7.2.1 Types of Greenhouse Gases

There are six different types of gases present in the atmosphere giving significant impact on the greenhouse effect:

- Carbon dioxide (CO_2)
- Methane (CH_4)
- Nitrous oxide (N_2O)
- Hydrofluorocarbons (HFCs)
- Perfluorocarbons (PFCs)
- Sulfur hexafluoride (SF_6)

These gases can be divided into two broad categories based on their presence in the atmosphere. Some of these gases are naturally present in the atmosphere, and concentration of these gases increases continuously due to human activities. CO_2, CH_4, and N_2O are examples of such gases. The other type of gases is not naturally present in the atmosphere and is created only due to human activities. Chlorofluorocarbons are examples of such gases.

Figure 7.1 shows the volume of GHGs emitted in the collective regions of Australia, Europe, the United Kingdom, and the United States, as reported by UNFCCC for the year 2012. From the figure, it can be commented that CO_2 stands for the highest position in the emission of radiation responsible for global warming, accounting for approximately 81%, followed by CH_4 (≈10%), N_2O (≈6%), and fluorides (≈2%).[5]

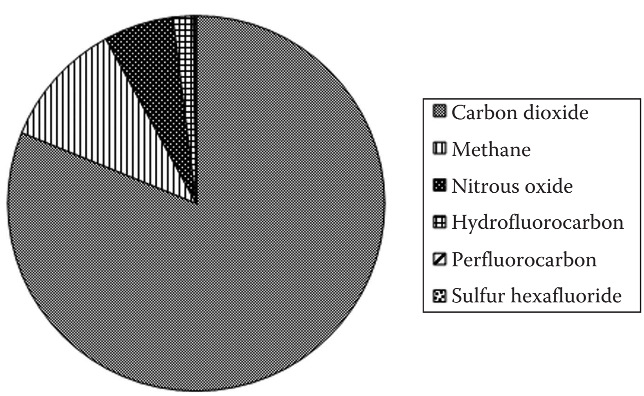

FIGURE 7.1 Emission of GHGs in 2012. (From Hertwich, E.G. and Peters, G.P., *Environ. Sci. Technol.*, 43, 6414, 2009.)

7.2.2 Sources of Greenhouse Gases

Many sectors emit GHGs that affect the natural environment. The following list gives some of these sectors that play a major role in the emission of GHG:

- Residential sector
- Industrial sector
- Commercial sector
- Transportation
- Agricultural sources
- Waste management

Transportation accounts for 12% of total emission of GHG in Australia. It has been reported that the emission of GHGs due to domestic transport increased by 27% between 1990 and 2006. Studies reported that public transport can minimize energy per passenger per kilometer by 65% as compared to a motor vehicle.[6] According to the regulation imposed by the IPCC, the United Kingdom should reduce GHG by at least 80% by 2050 in various sectors, including industries like aviation

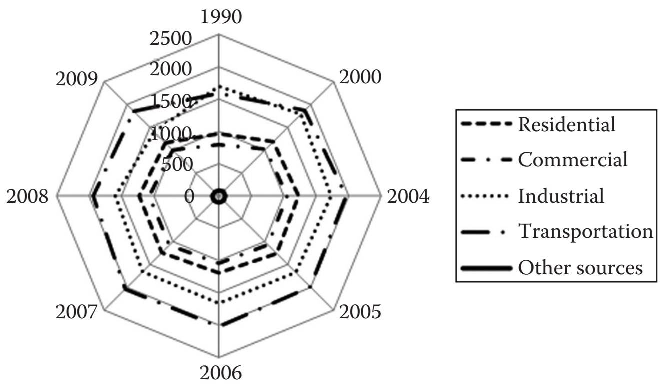

FIGURE 7.2 Emission of carbon dioxide by different sectors. (From U.S. Census Bureau, Statistical abstract of the United States: 2012, pp. 221–242.)

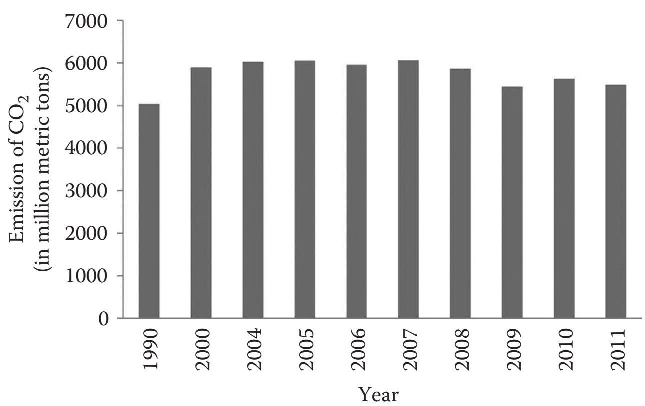

FIGURE 7.3 Year-wise emission of carbon dioxide in the United States. (From U.S. Census Bureau, Statistical abstract of the United States: 2012, pp. 221–242.)

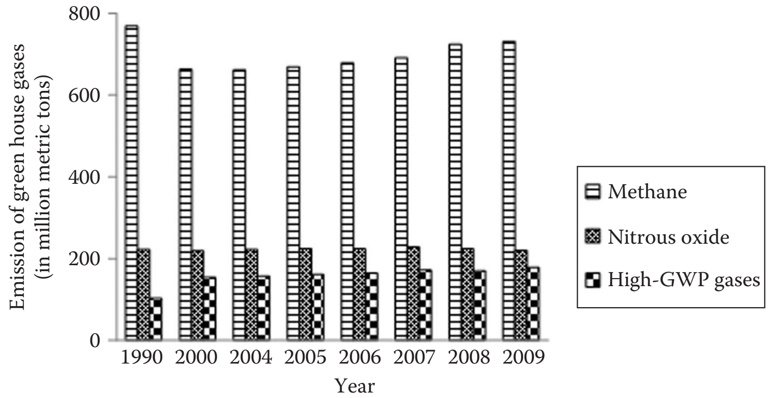

FIGURE 7.4 Year-wise emission of GHG in the United States. (From U.S. Census Bureau, Statistical abstract of the United States: 2012, pp. 221–242.)

and shipping. From 2011 onward, all flights arriving and departing from EU airports have been covered under these regulations.[7]

In India, the total emission of GHG in 2007 was around 1727.71 million tons, among which 57.8% GHG emission resulted from the energy sector, which includes transportation, electricity, residential, and others.[13] Figure 7.2 shows the emission of CO_2 by different sectors. It is clear that the transportation sector plays a vital role in the emission of CO_2, followed by industrial, residential, commercial, and other sources.

Figures 7.3 and 7.4 show the total emission of CO_2 and other GHGs from 1990 to 2009 in the United States. It can be noticed from these figures that the emission of CO_2 was much higher in volume than the emission of other gases.

7.3 CARBON FOOTPRINT

Carbon footprint is the term used to evaluate the total emission of GHGs by human activities. Few other terms are also used to quantify the emission of GHG and slightly vary in their method of measurement and system of representation. The following section gives the definition of different terms that are regularly used in the field of carbon footprint.

7.3.1 Definition of Carbon Footprint and Other Related Parameters

7.3.1.1 Global Warming Potential

Global warming potential (GWP) is a relative measure of how much heat a GHG traps in the atmosphere to contribute toward global warming and compares the amount of heat trapped by a certain mass of the gas under study to the amount of heat trapped by a similar mass of CO_2. This system of representation may be useful when we evaluate the condition of nature over a long period of time. GWP is the relative effect of climate change over a certain period of time. For example, for 20 years of duration, it can be represented as GWP_{20} and for 100 years, GWP_{100}.[9]

7.3.1.2 Carbon Footprint

Carbon footprint is the measurement of the amount of GHG produced through burning of fossil fuels for electricity, heating, transportation, etc., and it is expressed in terms of tons or kilogram or gram CO_2 equivalent.[9] It can be calculated in terms of GWP using the following equation:[9]

$$\text{Climate change} = \sum_i \text{GWP}_{a,i} \times m_i \tag{7.1}$$

where

$\text{GWP}_{a,i}$ is the GWP for the substance i integrated over a specified number of years
m_i (kg) is the quantity of substance i emitted

The result is expressed in kilogram or tons of the reference substance, CO_2.

7.3.1.3 Energy Intensity

It is defined as the ratio of total energy consumption to gross domestic product (GDP).[10]

7.3.2 Global Carbon Footprint and Its Effects

The world's average emission of GHG per capita is around 5.8 tons CO_2.[13] The carbon footprint of countries like UAE, Luxembourg, the United States, and Australia is much higher than the world's average value when emission of GHG per capita is considered. In Singapore, the emission of CO_2 had reduced by 53% in 2008 as compared to the highest emission in 1997.[11] The decrease in emission of CO_2 with respect to per capita was up to 64% during this period. Even though the per capita actual rate was reduced to 6.8 tons/year, the emission of CO_2 was above Asia's average emission of CO_2 (3.3 tons/year/capita) and much higher than the world's average.[11] By 2030, New York has targeted to reduce its citywide CO_2 emissions by 30% than the emission level in 2005.[12] On the other hand, per capita emission of developing countries like India is far lower than some of the other developing and developed countries. In India, per capita emission of CO_2 in the year 2007 was around 1.5 tons/year, which is much lower than the world's average. All over the world, 1.5 billion people are in short supply of electricity and around 27% of these people (404.5 million) are living in India.[13] Use of less electricity is responsible for lower per capita CO_2 emissions in India. In 2007, combustion of fossil fuel accounted for 93% of energy consumption in China.[10]

Agriculture accounts for around 14% of total GHG emission contributing to 52% of CH_4 emitted all over the world and around 84% of world's N_2O emission. N_2O is capable of trapping 310 times higher heat than the heat trapped by CO_2 and CH_4 is able to trap 21 times more heat than CO_2.[14]

IPCC identified that combustion of fossil fuel is one of the major sources of CO_2 emission leading to global warming. In 1997, the Kyoto Protocol was signed, and according to this, 37 industrialized countries are supposed to reduce their GHG emission in the period of 2008–2012 by 5.2% lower than the GHG emission in 1990.[14]

Figures 7.5 and 7.6 show the carbon footprint of different countries in the world in 2001.[5] In this study, GHG emissions associated with the final consumption of goods and services in eight different sectors such as construction, shelter, food, clothing, mobility, manufactured products, services, and trade were quantified. From these figures, it can be seen that Europe records the highest carbon footprint and Africa gives the lowest carbon footprint when the volume of GHG emission is considered (Figure 7.5). But when the emission of GHG per capita is considered, Australia stands for the highest, followed by Europe, North America, Africa, South America, and Asia.[5]

Some of the effects of increase in the emission of GHGs are as follows[1]:

- Effects of heat waves and other extreme events (cyclones, floods, storms, wildfires)
- Changes in patterns of infectious disease
- Effects on food yields

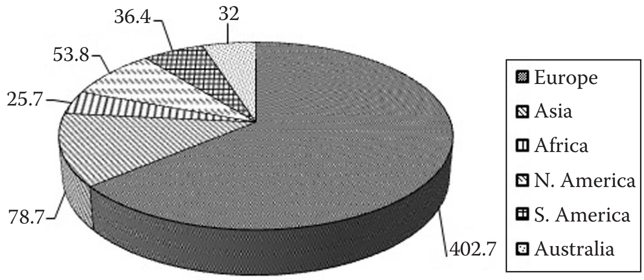

FIGURE 7.5 Carbon footprint of various parts of the world (ton/year). (From Hertwich, E.G. and Peters, G.P., *Environ. Sci. Technol.*, 43, 6414, 2009.)

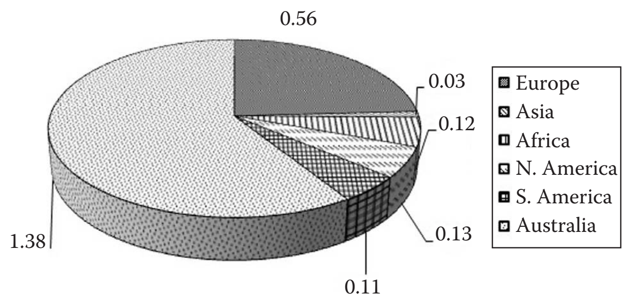

FIGURE 7.6 Carbon footprint per capita of various parts of the world (ton/year). (From Hertwich, E.G. and Peters, G.P., *Environ. Sci. Technol.*, 43, 6414, 2009.)

- Effects on freshwater supplies
- Impaired functioning of ecosystems (e.g., wetlands as water filters)
- Displacement of vulnerable populations (e.g., low-lying island and coastal populations)
- Loss of livelihoods[1]

7.4 CARBON FOOTPRINT OF VARIOUS TEXTILE PROCESSES

Textile industry is identified as one of the largest producers of GHG all over the world.[15] Kissinger et al. reported that textiles and aluminum generate the highest GHG emission per unit of material.[15] The textile industry is indicated as the fifth largest contributor of CO_2 emission.[16,17] In 2008, the global production of textiles reached 60 billion kg of fabric. It had consumed around 1074 billion kW h of electricity (which is equivalent to 132 million tons of coal) and approximately 9 trillion liters of water. Among the total consumption of electricity for textiles, only 15%–20% was consumed in the production of textiles and most of the remaining electricity was consumed in laundering processes. Electrical energy was reported to be one of the major energy consumption sectors in the textile industry.[18] Electrical energy is primarily spent for the following processes:

- Driving machinery
- Cooling
- Temperature control
- Lighting and office equipments

The electrical energy breakdown for a composite plant is shown in Table 7.1. It can be seen from the table that the spinning industry takes the major share of electricity with 41%, followed by weaving and wet processing units.[18,19]

TABLE 7.1
Typical Breakdown of Electricity Use in Composite Textile Industry

Sector	Electrical Energy Consumption (%)
Spinning	41
Weaving preparatory	5
Weaving	13
Humidification	19
Wet processing	10
Lighting	4
Others	8

Source: Choudhury, A.K.R., *Text. Prog.*, 45, 3, 2013.

TABLE 7.2
Machine-Wise Breakdown of Electrical Energy in Spinning Industry

Machine	Electrical Energy Consumption (%)
Blow room	11
Carding	12
Drawing machine	5
Combing machine	1
Simplex	7
Ring spinning machines	37
Open end machines	20
Winding machine	7

Source: Choudhury, A.K.R., *Text. Prog.*, 45, 3, 2013.

Table 7.2 shows the machine-wise electrical energy breakdown in the spinning sector. From the table, it can be seen that the spinning machines, namely, ring and open end spinning, jointly consume more than 50% of the energy consumed in the spinning industry.

Table 7.3 shows the percent share of global consumption of different types of textile fibers all over the world in 2008. From the table, it is clear that polyester and cotton stand for more than 75% of global consumption.[16] Therefore, the carbon footprint of textile industries mostly comes from the production, processing, and use of the products made from these fibers.

Recycling of textile materials is an important process in the textile industry that has a strong impact on the carbon footprint. The recycling industry diverts approximately 10 lb/capita or 2.5 billion lb of postconsumer waste from landfill.[20] In the United States, 70 million lb of scrap is deposited as landfills annually.[21] In Japan, around 2 million tons/year of textiles are sent to landfills. In the United Kingdom, around 3.3 million tons/year of textiles are recovered in which around 2 million tons are exported to other developing countries and 1.2 million tons of textiles are recycled. Around 70% of the world population mainly uses secondhand clothes.[22] Wool is comparatively easy to recycle than other fibers. In the United Kingdom, 40% of the wool garments are recycled, 7% of wool garments are incinerated, and 53% are disposed as landfill.[22] It has been reported that the energy required for the reuse or recycling process of polyester is only 1.8% of the total energy consumed by the virgin fiber. Also, reuse of 1 ton of cotton fiber needs only 2.6% of the energy required for the virgin material.[23] Therefore, recycling and reuse are important processes to reduce

TABLE 7.3
Global Consumption of Textile Substrates

Fiber	Consumption (%)
Polyester	39
Cotton	36
Polyamide	6
Other cellulosic fibers	5
Acrylics	3.5
Wool	2
Silk	0.2
Other fibers	8.3

Source: Athalye, A., Carbon footprint in textile processing, 2012, http://www.fibre2fashion.com, Accessed March 18, 2014.

carbon footprint of textiles. Some examples of the applications of recycled materials are as follows: T-shirts can be used as wipes and polishing clothes, fibers recovered from carpet waste can be produced as nonwovens and mats, and polymers from carpet melt can be used for automotive and other consumer products and also for matrix of composite materials.[24]

7.5 CARBON FOOTPRINT OF NATURAL FIBERS AND THEIR PRODUCTS

The emission of CO_2 in case of natural fibers occurs during preparation, planting, and field operations (weed control, mechanical irrigation, pest control, and fertilizers), harvesting, and yields. During production of natural fibers, normally two types of fertilizers are used such as manure and synthetic chemicals. The use of synthetic fertilizers is a main component of conventional agriculture leading to significant carbon footprint. The production of 1 ton of nitrogen fertilizer emits approximately 7 tons of CO_2 equivalent GHG.[25,26]

According to studies carried out by the Stockholm Environment Institute on behalf of the Bio Regional Development Group,[25] the energy used and CO_2 emitted to manufacture 1 ton of fiber is much higher for synthetic than natural fibers (cotton and hemp). The details of CO_2 emission of various natural fibers as well as polyester fiber are provided in Table 7.4.

TABLE 7.4
Kilogram of CO_2 Emissions per Ton of Spun Fiber

	Crop Cultivation	Fiber Production	Total
Polyester (USA)	0.00	9.52	9.52
Cotton, conventional (USA)	4.20	1.70	5.90
Cotton, organic (USA)	0.90	1.45	2.35
Cotton, organic (India)	2.00	1.80	3.80
Hemp, conventional	1.90	2.15	4.05

Sources: http://www.sei-international.org/mediamanager/documents/Publications/SEI-Report-EcologicalFootprintAndWaterAnalysisOfCottonHempAndPolyester-2005.pdf, accessed on March 10, 2014; http://oecotextiles.wordpress.com/2011/01/19/estimating-the-carbon-footprint-of-a-fabric/, accessed on March 10, 2014.

Natural fibers, in addition to having lesser carbon footprint[25] in the production of spun fiber,[25,26] have several additional advantages:

- Fibers are capable of being degraded by microorganisms (biodegradation) and composted (improving soil structure); in this way the fixed CO_2 in the fiber will be released and the cycle will be closed.
- Sequestering carbon: sequestering carbon is the process through which CO_2 from the atmosphere is absorbed by plants through photosynthesis and stored as carbon in biomass such as leaves, stems, branches, roots, and soils. For instance, 1 ton of dry jute fiber leads to absorption of 2.4 tons of carbon.[26]

Producing cotton fibers through organic way provides lot of advantages over conventional process such as less GHG emission, use of less energy for production, and environmental benefits.[25,26] According to a study published in Innovations Agronomiques (2009), organic agriculture emits 43% lesser GHG than conventional agriculture. The research carried out by Cornell University revealed that organic farming required just 63% of energy required for conventional farming. In addition, it is found that organic farming adds 100–400 kg of carbon per hectare to the soil each year and when this stored carbon is included in the carbon footprint, it reduces the total GHG even further.[25,26]

In case of the life cycle of cotton textiles, it is seen that about 50% of CO_2 emissions occur during fiber production, manufacturing of goods, trade, and transport and the remaining 50% are caused by daily usage. Figure 7.7 shows the key CO_2 sources during cotton textile manufacturing process from fiber to garment.[27]

In Europe, light oil and gas are the primary energy sources, but in China the preferred energy source is usually the coal. CO_2 emissions from natural gas are only around 50% of those produced when coal is used as the energy source (see Figure 7.8). In China, around 80% of electricity is produced by thermal power plants. As a result, textiles made in China have a carbon footprint that is around 40% greater than in Turkey, Europe, or South America, simply on the basis of the selected energy source.[27]

Within the full supply chain cycle of cotton textiles/garments (apart from the consumer use phase, i.e., washing and drying), the fiber manufacturing phase emits the most GHG. Cotton incorporated (2009) assessed that GHG emissions were around 1.8 kg CO_2e/kg of fiber. In a parallel study performed on Australian cotton, GHG emissions were assessed around 2.5 kg CO_2/kg of fiber,

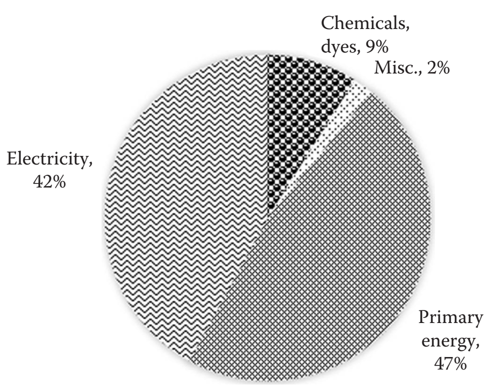

FIGURE 7.7 CO_2 sources within the textile value-added chain for a pair of trousers made of 100% cotton manufactured in China in 2012. (From Strohle, J., Textile achieve ecological footprint new opportunities for China, http://www.benningergroup.com/uploads/media/Carbon_Footprint_China_EN.pdf, accessed on March 10, 2014.)

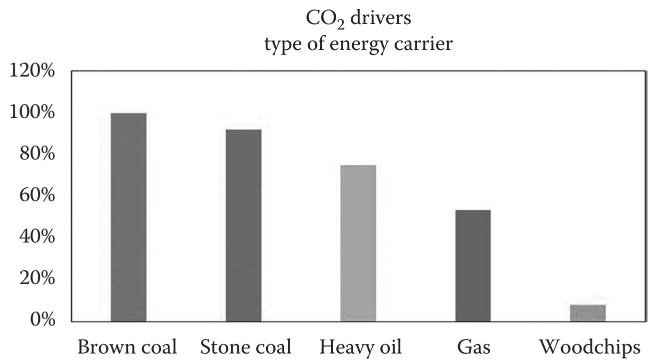

FIGURE 7.8 CO_2 emissions for different energy sources. (From Strohle, J., Textile achieve ecological footprint new opportunities for China, http://www.benningergroup.com/uploads/media/Carbon_Footprint_China_EN.pdf, accessed on March 10, 2014.)

including emissions from fertilizers, chemicals, fuel, and electricity. The GHG emissions in three cotton farming systems, among which one was an irrigated system and the other two were dryland farming systems in Queensland, Australia were assessed. Estimation considering emissions from transportation of farm inputs (farm machinery, agrochemicals, and fertilizers), production, packing and storage, production, extraction, and use of electricity for irrigation, and N_2O emissions from soils due to N-fertilizer usage, revealed that GHG emission was lowest from dryland double skip (1376 kg CO_2e/ha), slightly higher from dryland solid plant (1376 kg CO_2e/ha), and the highest from irrigated cotton farming (4841 kg CO_2e/ha).[28]

Textile finishing is an important process for cotton textiles leading to significant amount of carbon footprint. CO_2 emissions are caused directly by the energy consumers and indirectly by the consumable such as lubricants and chemicals. The dissemination of CO_2 emissions in a fully continuous textile finishing process for cotton textiles shows that about 40% comes from washing and steaming, 50% comes from drying, and 10% from the use of chemicals. In knitwear finishing using the exhaust process, the largest part of emissions, that is, 60%, is caused by heating of water.[27] Table 7.5 provides details of energy consumption in cotton or cotton blend finishing process.

TABLE 7.5
Energy Consumption in Cotton or Cotton Blend Finishing Process

Process/Consumer	Primary Source of Energy Used	CO_2 Emissions
Singeing	Gas	Low
Washing/heating energy	Steam	Very high
Steaming/reaction processes	Steam	Moderate
Drying	Gas/coal/steam	Very high
Fabric transport	Electricity	Low
Air conditioning technology/exhaust air	Electricity	Low
Chemicals	No date	Low

Source: Strohle, J., Textile achieve ecological footprint new opportunities for China, http://www.benningergroup.com/uploads/media/Carbon_Footprint_China_EN.pdf, accessed on March 10, 2014.

7.5.1 Carbon Footprint of Cotton Fiber Products

Studies reported that the highest CO_2 emissions in case of cotton clothing (e.g., T-shirt) occur during the usage phase of the garment. Also, significant GHG emissions occur during the production of raw materials.[29] As shown in Figure 7.9, the least GHG-intensive processes in case of cotton T-shirt life cycle are fabric and garment production processes besides product disposal stage. This figure also reveals the rough equivalence between GHG emissions and energy use in the garment life cycle. According to another study, CO_2 emissions in different stages of cotton T-shirt life cycle are presented in Figure 7.10. It can be noticed that a major improvement in terms of GHG emissions

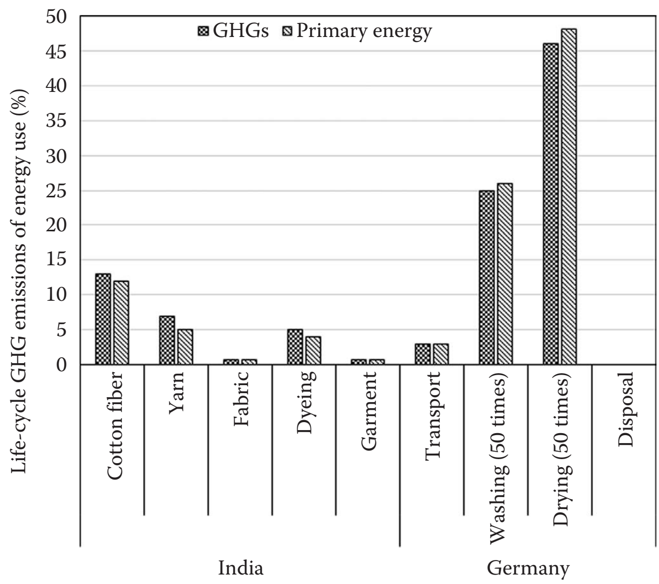

FIGURE 7.9 Garment life cycle GHG emissions of cotton T-shirt. (From Strohle, J., Textile achieve ecological footprint new opportunities for China, http://www.benningergroup.com/uploads/media/Carbon_Footprint_China_EN.pdf, accessed on March 10, 2014.)

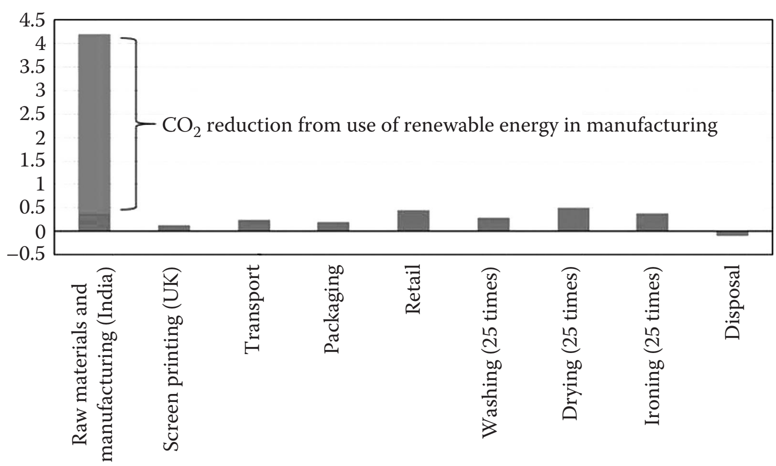

FIGURE 7.10 Garment life cycle GHG emissions of cotton T-shirt, showing amount of CO_2 per stage. (From Strohle, J., Textile achieve ecological footprint new opportunities for China, http://www.benningergroup.com/uploads/media/Carbon_Footprint_China_EN.pdf, accessed on March 10, 2014.)

can be achieved through the use of renewable energy in production processes. Besides production of raw materials and fabric, various processes responsible for GHG emissions are printing, transport, packaging, retail, washing, drying, and ironing.[30] According to this study also, use phase is the major cause of GHG emissions, causing nearly 50% of the actual total.[29]

7.5.1.1 Carbon Footprint of White Long Shirt

Figure 7.11 shows the carbon footprint of white long shirt made of cotton. To produce these long shirts, raw materials were cultivated in the United States and garments were made in Bangladesh for German customers. The estimated carbon footprint of this cotton product during its life cycle was 10.75 kg CO_2e.[30]

Carbon footprint due to cotton growing including ginning is up to 1.27 kg CO_2e. As shown in Figure 7.12, almost half of the emissions are caused by direct and indirect N_2O, which has a GWP of 298 relative to CO_2. Direct emissions of N_2O depend on soil structure, the use of fertilizer, water, temperature, etc. The manufacturing phase leads to an emission level of 3.0 kg CO_2e per functional unit during shirt production. CO_2 emissions in the production stage of the shirt are shown in Figure 7.13. Approximately 1/3 of the carbon emissions are caused by heating processes and 2/3 by electricity. CO_2 emissions in the distribution processes are shown in Figure 7.14. During the distribution phase, CO_2e emission is 87 kg, which is more than half resulting from returns by customers.

It was observed in this study that consumers can contribute significantly to reduce the carbon footprint of the products. Use of energy-efficient devices can significantly reduce the carbon footprint during the use phase. Household devices with a better level of energy efficiency may decrease the carbon footprint in the use phase by one-third as compared to the household stock. Also, the carbon footprint in the use phase is influenced by the washing temperature and actual loading of

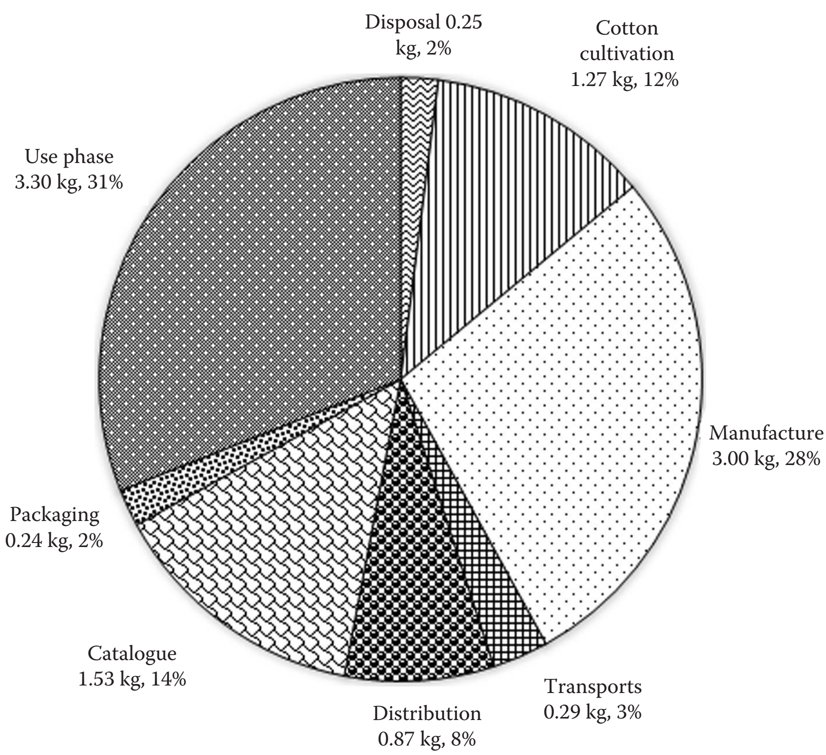

FIGURE 7.11 Carbon footprint of cotton white long shirt during its life cycle. (From Jungmichel, N., *The Carbon Footprint of Textiles*, Systain Consulting, Berlin, Germany, 2010.)

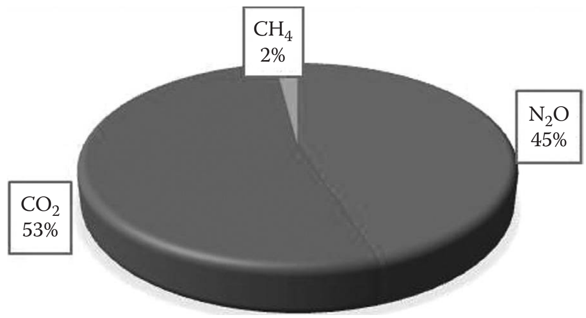

FIGURE 7.12 Different GHG emissions during cotton growing. (From Jungmichel, N., *The Carbon Footprint of Textiles*, Systain Consulting, Berlin, Germany, 2010.)

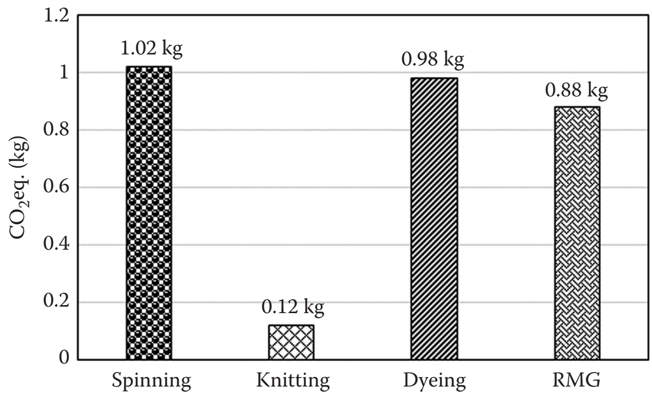

FIGURE 7.13 CO_2 emission in the production process of a shirt. (From Jungmichel, N., *The Carbon Footprint of Textiles*, Systain Consulting, Berlin, Germany, 2010.)

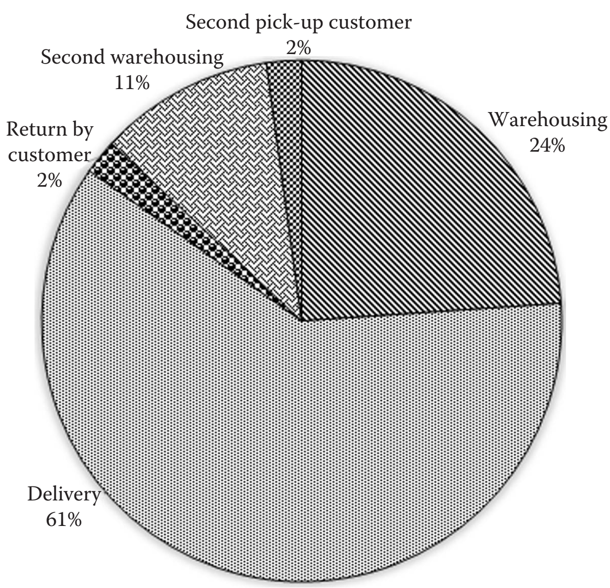

FIGURE 7.14 CO_2eq. emissions during the distribution process. (From Jungmichel, N., *The Carbon Footprint of Textiles*, Systain Consulting, Berlin, Germany, 2010.)

appliances. It was observed that a washing temperature of 40°C instead of 60°C could cut the carbon footprint of the use phase by 45% and 30°C instead of 40°C by 40%.[30]

7.5.1.2 Comparison of Carbon Footprint of Different Cotton Products

Studies also compared the carbon footprint of different cotton products and also with products made with synthetic fibers, as shown in Figure 7.15. The details of these products are provided in Table 7.6. The carbon footprint of the three products during their life cycle is presented in Figure 7.16.

It can be noticed from Figure 7.16 that the acrylic jacket has lower carbon footprint in the manufacturing and use phases as compared to the cotton products. However, disposal of acrylic good leads to significantly higher CO_2 emissions than the cotton products. Among the cotton long shirt and sweat jacket, the long shirt gives a lower carbon footprint in raw material, manufacturing, and disposal phases, but a higher carbon footprint in the distribution phase.

7.5.2 Carbon Footprint of Wool Fiber and Products

According to studies, the energy required for wool production is 38 MJ/kg. New Zealand Merino study estimated an energy usage of 46 MJ/kg to produce wool top, half of which is used in the farm and CO_2 emission for production of wool staples is 2.2 kg CO_2/kg (considering 50 g CO_2/MJ of energy).[31] The energy consumption and CO_2 emission of wool fiber are compared with other

(a) (b) (c)

FIGURE 7.15 Three different textile products: (a) cotton long shirt, (b) sweat jacket with hood, and (c) jacket for kids. (From Jute Eco-label: Life cycle assessment of jute products, 2006, http://www.jute.com:8080/c/document_library/get_file?uuid=e39c1527-75ed-47e9-9c88-c415ac11cf09&groupId=22165, accessed on November 25, 2013.)

TABLE 7.6
Details of Three Different Products

White Long Shirt	Sweat Jacket	Jacket for Kids
100% cotton (USA)	100% cotton (Africa)	100% acrylic
Net weight—222 g	Net weight—446 g	Net weight—266 g
Cotton from the United States, production in Bangladesh, offered by OTTO	Cotton from Benin, production in Turkey, offered by BAUR	Acrylic from China, production in Bangladesh, offered by OTTO

Source: Jungmichel, N., *The Carbon Footprint of Textiles*, Systain Consulting, Berlin, Germany, 2010.

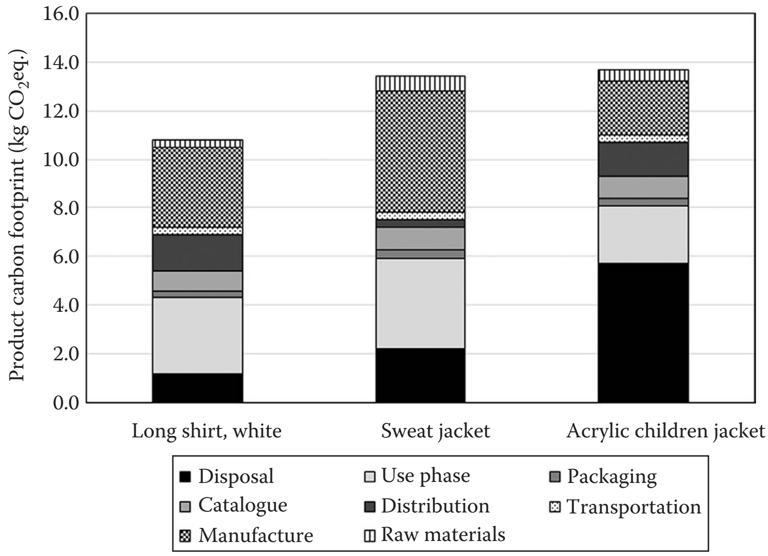

FIGURE 7.16 Carbon footprint of three different textile products during its life cycle. (From Jungmichel, N., *The Carbon Footprint of Textiles*, Systain Consulting, Berlin, Germany, 2010.)

TABLE 7.7
CO_2 Emissions in kg/kg of Different Textile Fibers Based on Energy Consumption (kW h/kg Fiber)

Fiber Type	Energy Consumption kW h/kg Fiber	CO_2 Emissions in kg/kg Fiber
Nylon	69	37
Acrylic	49	26
Polyester	35	19
Polypropylene	32	17
Viscose	28	15
Cotton	15	8
Wool	13	7
Hemp	5	3

Source: http://www.metrocon.info/images/uploads/SWhittaker-METROCON12.pdf, accessed on March 11, 2014.

textile fibers in Table 7.7. It can be noticed that wool fiber consumes lower energy and also leads to lower carbon footprint than the other listed fibers, except hemp fibers, which have the lowest carbon footprint.

7.5.3 Carbon Footprint of Jute Fiber and Products

The emission of GHG of a jute fiber yarn in different phases such as cultivation and retting phase, manufacturing phase, and product disposal phase has been studied and listed in Table 7.8 for 684 tons of jute yarn. This study considered the credits of jute product incineration for energy production to replace fossil fuel utilization and took into account only 50% of CH_4 emission considering capture of the remaining 50% during jute product disposal through landfill.[33]

It can be concluded from these results that the overall GHG emission effect in the cultivation and retting phase is negative. This implies that the jute plantation process acts as a carbon absorber.

TABLE 7.8
Impact of GHG Effect of Jute Fiber at a Different Phase of the Life Cycle

Phase	IPCC–GHG Effect (Direct 100 Years)	Value	Unit
Cultivation and retting phase of final raw jute	CO_2, CO_2 equivalent CH_4	−4,502,370	g·eq. CO_2
Manufacturing phase	CO_2, CO_2 equivalent CH_4	485.71	g·eq. CO_2
Disposal of product through incineration	CO_2, CO_2 equivalent CH_4	−6.895	g·eq. CO_2
Disposal of product through landfill	CO_2, CO_2 equivalent CH_4	14.124	g·eq. CO_2

Source: Jute Eco-label: Life cycle assessment of jute products, 2006, http://www.jute.com:8080/c/document_library/get_file?uuid=e39c1527-75ed-47e9-9c88-c415ac11cf09&groupId=22165, accessed on November 25, 2013.

Even though the emission of CH_4 during the retting process contributes to the GHG impact, this effect is balanced by the carbon sequestration of jute plants during their farming. The manufacturing phase contributes to the GHG effect due to CO_2 emissions resulting from the use of fossil fuel, electricity, and transportation. It can be also noted that the disposal of jute products into an unmanaged landfill leads to the GHG effect due to CH_4 emission. Conversely, this impact reduced considerably when the disposal of the jute product is done through incineration to produce energy for replacement of fossil fuel–based energy.[33]

7.5.4 Carbon Footprint of Linen Fiber Products

The linen shirt studied in this research was manufactured in China for use in France. It can be noticed from Figure 7.17 that primary energy is not always a good representation for GHG emissions depending on the type of energy source used. Figure 7.18 illustrates the relative GHG

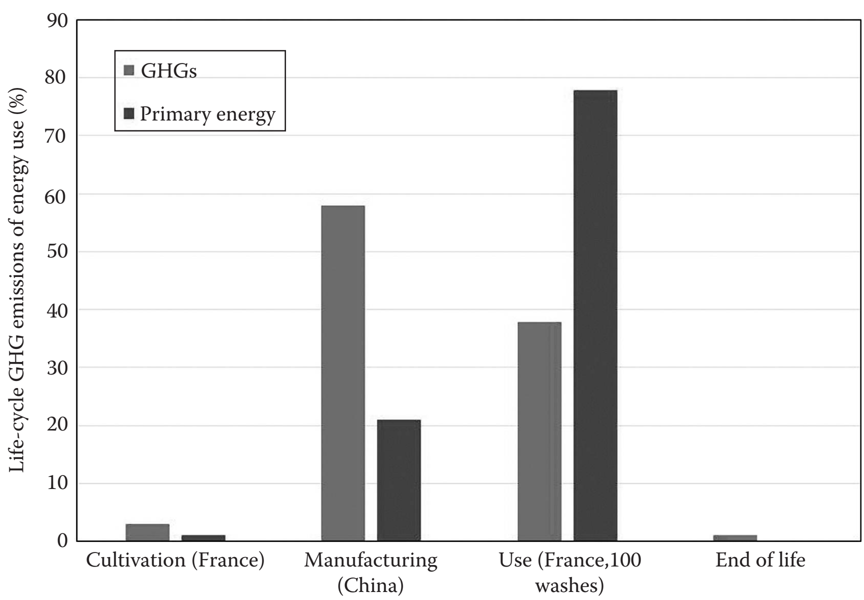

FIGURE 7.17 Garment life cycle GHG emissions of linen shirt. (From Strohle, J., Textile achieve ecological footprint new opportunities for China, http://www.benningergroup.com/uploads/media/Carbon_Footprint_China_EN.pdf, accessed on March 10, 2014.)

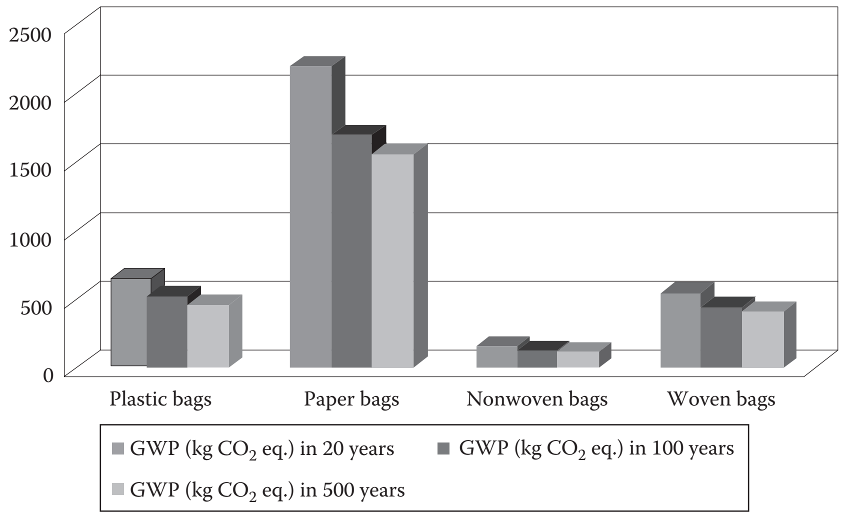

FIGURE 7.18 Carbon footprint results without usage and disposal option in China and Hong Kong. (From Muthu, S.S. et al., *Atmos. Environ.*, 45, 469, 2011.)

emissions produced by a linen shirt during its manufacturing process. Since the linen shirt was manufactured in China, where coal-fired power plants produce most of the used electricity, the amount of GHG emissions is high. On the contrary, during its use in France, a low amount of GHG is emitted due to the use of nuclear power as the energy source.[29] Higher energy is necessary in the use phase of the linen shirt due to the high-energy requirement to iron the linen shirt. It can also be noticed that cultivation of raw material (flax) leads to low amount of energy use and GHG emissions.[29]

7.6 CARBON FOOTPRINT OF SYNTHETIC FIBERS AND THEIR PRODUCTS

In the case of synthetic fiber, the key factor related to carbon footprint is that the fibers are produced from fossil fuels. The extraction of oil from the earth and the production of synthetic polymers require a high amount of energy and therefore emit a much higher amount of CO_2 as compared to natural fibers (refer to Table 7.4).

Acrylic fiber requires 30% more energy during its production than polyester and for nylon it is even higher. Not only the quantity of GHG emissions is of prime concern for synthetic fibers, but also the type of GHGs produced is important. Nylon, for example, emits N_2O, which is 300 times more damaging than CO_2 and because of its long life, it can reach and diminish the layer of stratospheric ozone.[25,26] Moreover, synthetic fibers do not decompose and in landfills they release heavy metals and other additives into the soil and groundwater. Recycling needs expensive separation, while burning produces pollutants. In the case of HDPE, 3 tons of CO_2 is emitted due to burning of 1 ton of material.[25,26]

7.6.1 Carbon Footprint of PP Shopping Bags

Nonwoven shopping bags, mostly made of polypropylene fiber, are popular and are commonly used as a reusable item. The process of manufacturing polypropylene (PP) bags starts from fiber production followed by spun bonding and different steps of bag manufacturing such as cutting, screen printing, sewing, and packaging. Shopping bags are made using two different methods, namely, the sewing process (A), that is, joining two sides of the bags by stitching, and thermal bonding (B), that is, joining two sides of the bags through heat application.[34] The results of the carbon footprint evaluated for these two types of shopping bags through the IPCC 2007 GWP V 1.1 method for 100- and 20-year time periods are presented in Table 7.9. It was observed that the shopping bag produced through the sewing process had a lower carbon footprint as compared to the one produced through the thermal bonding process.

Studies also compared the carbon footprint of different types of shopping bags used in China, Hong Kong, and India such as plastic, paper, nonwoven (PP), and woven cotton bags. GHG emissions of these shopping bags are listed in Tables 7.10 and 7.11.[1]

The results of life cycle impact assessment (LCIA) performed using the IPCC 2007 method to evaluate the carbon footprint of these shopping bags (without considering usage and disposal) in

TABLE 7.9
GWP Potentials

Impact Category, Unit	A	B
IPCC GWP 100 a, kg CO_2 eq.	60.7	86.3
IPCC GWP 20 a, kg CO_2 eq.	62.5	88.6

Source: Muthu, S.S. et al., *Fibers Text. Eur.*, 3(92), 12, 2012.
100 a, 100 years; 20 a, 20 years.

TABLE 7.10
Life Cycle Inventory Data of Plastic, Paper, Nonwoven, and Woven Bags in China and Hong Kong

Alternative	Weight/Bag (g)	Bags/Year	Material Consumption	GHG Emissions (CO_2 eq.) (kg)	Primary Energy (MJ)
Plastic bag	6	1095	6.57 kg	12.8	442.2
Paper bag	42.6	1095	46.65 kg	24.8	1518.3
PP fiber nonwoven bag	65.6	10.95	718. 32 g	5.17	122.2
Woven cotton bag	125.4	21.9	2.75 kg	6.06	385

Source: Muthu, S.S. et al., *Atmos. Environ.*, 45, 469, 2011.

TABLE 7.11
Life Cycle Inventory Data of Plastic, Paper, Nonwoven, and Woven Bags in India

Alternative	Weight/Bag (g)	Bags/Year	Material Consumption	GHG Emissions (CO_2 eq.)	Primary Energy (MJ)
Plastic bag	6	150	900 g	1.74 kg	60
Paper bag	42.6	150	6.39 kg	3.41 kg	210
PP fiber nonwoven bag	65.6	1.5	98.4 g	708 g	16.73
Woven cotton bag	125.4	1.3	376.2 g	831 g	52.74

Source: Muthu, S.S. et al., *Atmos. Environ.*, 45, 469, 2011.

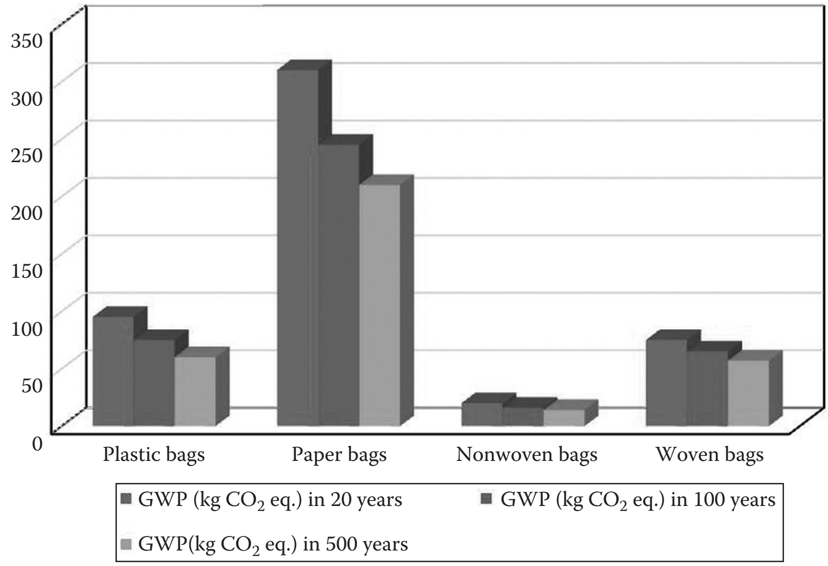

FIGURE 7.19 Carbon footprint results without usage and disposal option in India. (From Muthu, S.S. et al., *Atmos. Environ.*, 45, 469, 2011.)

terms of GWP of 20 years, 100, and 500 years are presented in Figures 7.18 and 7.19. The results show that nonwoven bags made of PP performed better than other bags, followed by woven cotton bags. Paper and plastic bags have very high GWP for 20, 100, and 500 years compared to nonwoven (PP) and cotton woven bags. It can be seen that nonwoven bags consume lesser energy and materials and also emit a lower amount of GHG as compared to other shopping bags used in China, Hong Kong, and India.[1]

7.6.2 Carbon Footprint of Products Produced from Regenerated Fibers

The carbon footprint of products produced from the most commonly regenerated cellulosic fiber, that is, viscose rayon, has also been reported in the literature. One of such studies reported GHG emissions due to the production of Pashmina shawl in India, including the staple fiber production stage up to the manufacturing of this product.[35] Both direct and indirect GHG emissions were considered for carbon footprint evaluation. The direct GHG emissions included the emissions from the production site such as from electricity consumption and fuel combustion. On the other hand, indirect GHG emissions included the emissions from fiber production, that is, the embodied energy of fiber produced, transportation of raw materials and fuel to the production place, and transportation of Pashmina shawl from the production place to the warehouse, that is, the transportation of carbon footprint.[35] Potential sources of CO_2 for the manufacturing of this product, as identified in this study, were rayon staple fiber production (embodied carbon footprint), transportation of raw material (rayon staple fiber) and fuel (diesel/petrol) to the production site, transportation of produced Pashmina shawl from the production site to the warehouse (transportation carbon footprint), etc. Among these, manufacturing of rayon staple fiber (embodied carbon footprint) and production of Pashmina shawl were found to be the main sources of carbon footprint. Approximately 25% of carbon emissions in the total production process of one Pashmina shawl come from the dyeing and packing unit, whereas 57% come from the spinning and weaving units. Emissions from transportation and packing of Pashmina shawl were lesser. Table 7.12 provides the emission inventory data for shawl production.[35]

TABLE 7.12
Emission Inventory for Pashmina Shawl Production

Emission Inventory	kg CO_2/Pashmina Shawl
Fiber	1.6
Transportation	0.063
Manufacturing	0.8164
Chemicals	0.06
Packing	0.02
Total	2.5594

Source: Shawl, P., Product carbon footprint, http://www.ecotechenergy.in/pdf/carbon-footprint-pashmina-shawl.pdf, accessed on March 11, 2014.

7.7 MODERN STRATEGIES TO REDUCE CARBON FOOTPRINT OF TEXTILE PROCESSING

Carbon footprint reduction is an important issue for all human beings in order to protect our planet for our future generations. Our commitments toward future compel us to create a green and sustainable environment. With the growth of civilization, textiles become much more than a primary need for individuals. The per capita consumption of clothing increases exponentially with the improved living standard and fashion consciousness of the people.[20] As discussed in the previous sections, textile products create carbon footprint in each phase of their life cycle. The complicated supply chain of textile industry leads to significant amount of carbon footprint in its each segment. With a huge production volume, it is found to be one of the major sources of emissions of GHG globally.[36,37] In 2008, global textile production was estimated at 60 billion kg of fabric. The energy and water needed to produce that amount of fabric are 1074 billion kW h of electricity or 132 million metric tons of coal and 6–9 trillion liters of water.[37]

Looking into this huge consumption of energy and water, strategies have been initiated to reduce carbon footprints in textile processing. More and more energy-efficient processes are being used. The intermediate products and processes are improved with new innovations for lower carbon footprints. All the processing steps starting from harvesting to packing, transporting, usage, and disposal add carbon footprint to textiles.[1]

It is reported that other synthetic fiber production is more energy intensive.[38] Thus, the first corrective measure taken to reduce the carbon footprint is the use of natural fibers. Natural fibers have lower carbon footprint than the synthetic ones. Use of organic fibers further reduces the carbon footprint. The less energy-intensive processes create less carbon footprint. Natural fibers have other advantages like biodegradability and sequestering carbon from atmosphere.[39] DuPont came up with a fiber called Sorona having much lower carbon emission as compared to other synthetic fibers. Unlike most of the synthetic fibers, it is an agricultural product and not petrochemical derived. Sorona has high renewable ingredients content.

Energy- and water-intensive textile processing is the major contributor as far as carbon footprint is concerned. Strategies have been proposed to reduce the carbon footprint of textile processing. Low energy- and water-intensive processes and products are now commercially available in the market. Some of the initiatives are as follows: reduction of water consumption during pretreatment, dyeing, washing, and finishing is achieved through the use of low and ultralow liquor ratio machines. Less water leads to less energy for heating at different processing steps and also less effluent treatment load. A study carried out by Benninger shows that the reduction and reuse of water and energy is the key parameter to reduce carbon footprint in the textile industries.[27] The knitwear industries use a soft flow machine during processing that consumes high water and energy. Continuous dyeing and finishing machines for knitwear are the recent developments that reduce the water and energy usage to a significant level. A number of eco-efficient solutions have been introduced into the market that are environmentally friendly and contribute to saving of resources. The processing time and water consumption can be reduced with these chemicals as compared to the conventional systems. A one-step process of textile dyeing and finishing, combining the dyeing, washing, and finishing steps into one step, can reduce the processing time and energy cost. Consumption of nonrenewable energy can be reduced by preheating of water through solar energy or heat exchanger in waste water line. The heat loss is minimized by adequate insulation of processing machines and appropriate heat recovery systems. The caustic and water recovery plants reuse the water and alkali to a great extent and thus reduce the carbon load in processing.

The combined approach for processing helps in significant reduction of carbon footprint. Combined singing–desizing, desizing–scouring–bleaching, one bath dyeing of polyester/cotton blends, etc., reduce the number of textile processing stages and thereby reduce consumption of water and energy. Since the drying process takes a high amount of energy, all preparatory processes are carried out without drying, except the last stage where fabrics ready for dyeing or finishing are prepared. Continuous dyeing processes like cold pad batch (CPB) and thermosol require less water for dyeing. After dyeing, the washing process also has been improved with less number of wash chambers and wash liquor. The whole process saves water and energy. Continuous processing of knits is still under development. New processing techniques like waterless dyeing, CO_2 dyeing, foam dyeing, finishing, and coating are gradually gaining their acceptance in industries. A combination of water/air is tried successfully for dyeing that reduces the water consumption during dyeing. The cost associated with these processes is also reducing in recent years. Gaston Systems, USA, has developed a foam finishing machine that saves lots of water. To reduce carbon footprint, entire reprocessing of textile materials, which not only burdens the processing cost but also increases GHG emissions, needs to be avoided. Hence, right first time (RFT) and right every time (RET) dyeing performances are essential for reduction in carbon footprint of textile processing. Thus, advanced software to improve the lab to bulk conversion ratio are utilized by many industries.

Enzyme-based processing like desizing, scouring, bleach neutralizing, bio-softening, and post-dyeing wash-off is in the market. Enzyme suppliers are offering specialized products for combined processes to reduce the number of processing steps. These enzymes replace harsh chemicals used to remove impurities from the fiber or fabric. Their use reduces energy costs and water consumption and also improves the feel of the fabric. Cationic cotton is successfully utilized for salt-free dyeing with reactive and direct dyes. High fixation reactive dyes are useful for less carbon footprints. These dyes require reduced salt for high exhaustion. In the printing area, digital inkjet printings and low-temperature curing pigment printings are commercially available.[17] Huntsman has developed inks from the dyes to use in a digital printer directly for printing on fabrics. This digital printing process significantly reduces the environmental footprint as no water, salt, or other chemicals are required.

Apart from these technological advances, two significant strategies have been adopted for reduction in carbon footprints in the textile sector, namely, reuse and recycle of textiles. The recycle is effective only when the carbon loading to recycle is less than the disposal. Reuse of textile waste can be done in different ways. Some common practices are releasing clothes into the marketplace through secondhand shops and donating to some charity organizations or informally among family members. Reports indicate that large amounts of secondhand clothing are dispatched abroad for selling on the global market in Eastern Europe or Africa.[40] According to statistics, 26,000 tons of used garments and shoes were collected by charity organizations in Sweden during 2008 as donations to Africa and Eastern Europe.[41]

There are many ways to reduce the carbon footprint throughout the entire life cycle of textile products, and one of the promising ways to minimize the carbon footprint is to recycle the process waste instead of disposing at landfill and also to recycle the textile products at the end of life. Reuse of textile products has environmental benefits. However, the amount of energy saved and avoided emissions by applying reuse of discarded textiles, the amount of energy usage, and GHG emissions during collection, sorting, and reselling of the used clothes should be assessed and compared with the energy demand and emissions of manufacturing new products.[42] In the present decade, due to the alarming environmental impacts and other reasons such as rewards in terms of monetary benefits given to people when they return the product for recycling, governmental policies, etc., people have started supporting recycling activities as compared to the last decade.[23] Recycling is one of the proven and promising ways of reducing carbon footprint.[23] There are many strategies to recycle textile products, which can reduce carbon footprint. The use of life cycle analysis software is helpful for estimating the recycling potential of textile products.[9]

It is evident from the studies that the textile sector is highly energy intensive. The bulk of the carbon footprint of the textile industry is actually due to the usage of energy, and hence all strategies are directed toward using less energy, reuse of waste energy, and use of renewable sources of energy as far as possible.[43] During fiber production stage, more focus is on the use of organic natural fibers for their less carbon footprint as compared to synthetic ones.[26] Though the crop cultivation stage involves CO_2 emission for natural fibers, the production of synthetic fibers is a higher energy-intensive process and results in high CO_2 emission. Considering the carbon footprint addition due to transportation of raw materials and finished products,[1] composite textile mills and organic farming may be a good option for the future.

7.8 CONCLUSIONS

Carbon footprint is the measurement of the amount of GHG produced through burning of fossil fuels for electricity, heating, transportation, etc., and it is expressed in terms of tons or kg CO_2 equivalent. Various GHGs are CO_2, CH_4, N_2O, and CFC, and their emissions may result in serious problems such as heat waves and other extreme events (cyclones floods, storms, wildfires), changes in patterns of infectious disease, reduced food yields and freshwater supplies, impaired functioning of ecosystems, displacement of vulnerable populations, and loss of livelihoods. The textile industry is identified as one of the largest producers of GHG all over the world and has been reported to generate the highest GHG emission per unit of material. Electrical energy is one of the major energy consumption sectors in the textile industry, and electrical energy is spent for driving machinery, cooling, temperature control, lighting, and office equipment. Among the various textile industries, the spinning industry takes the major share of electricity with 41%, followed by weaving and wet processing units. The emission of CO_2 in case of natural fiber production occurs during preparation, planting, field operations (weed control, mechanical irrigation, pest control, and fertilizers), harvesting, and yields. However, energy used and CO_2 emitted to manufacture 1 ton of natural fiber are much lower as compared to synthetics fibers. In case of cotton textiles, 50% of CO_2 emissions occur during fiber production, manufacture, trade, and transport and the remaining 50% are caused by daily usage, that is, washing and drying. Textile finishing is an important process for cotton textiles leading to significant amount of carbon footprint resulted from CO_2 emissions of 40% from washing and steaming, 50% from drying, and 10% from the use of chemicals. Production of wool fiber uses lower energy and has lower carbon footprint as compared to cotton fibers. The plantation process of jute fibers acts as a carbon absorber, and although emission of CH_4 during the retting process contributes to the GHG impact, this effect is balanced by the carbon sequestration of jute plants during their farming. Cultivation of linen fibers also results in very less GHG emissions. However, higher energy is necessary in the use phase of linen products due to high energy requirements to wash, dry, and iron the linen materials. In case of synthetic fibers, extraction of oil from earth as well as production of synthetic polymers require high amount of energy and therefore emit much higher amount of CO_2 as compared to natural fibers. Among the synthetic fibers, nylon and acrylic leads to higher carbon footprint than polyester fibers. Potential sources of CO_2 emissions for the production of viscose rayon fiber products are rayon staple fiber production (embodied carbon footprint), transportation of raw material (rayon staple fiber) and fuel (diesel/petrol) to the production site, transportation of product from the production site to the warehouse (transportation carbon footprint), etc., and among these, manufacturing of rayon staple fiber (embodied carbon footprint) and products is main source of carbon footprint. In recent times, various modern strategies and processes are being practiced to reduce the carbon footprint of textile industries such as promoting more use of natural fibers; reduction of water consumption during pretreatment, dyeing, washing, and finishing through the use of low and ultralow liquor ratio machines; combining dyeing, washing, and finishing steps into one step; use of continuous dyeing processes like CPB and thermosol; new processing techniques like waterless dyeing, CO_2 dyeing, foam dyeing, finishing and coating; enzyme-based processing like desizing, scouring, bleach neutralizing, bio-softening, and postdyeing wash-off; and reuse and recycle of textile goods.

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