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Prospects and Constraints for Designing a Sustainable 'T-Shirt': A Life Cycle Analysis

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Abstract Nowadays sustainable or green product is using as a 'fashion word' in almost all economic and business related fields. Although sustainability of a product is a complex multifunctional approach and interlinked with social, cultural, political, technological, gender and environmental aspects but in most cases it only focuses on raw materials. The aim of this review paper was to speculate the sustainability of a cotton made 'T-Shirt', a textile commodity by using Life Cycle Assessment (LCA) tool. The input-output based analysis of its most significant indicators water, energy, land and labor are illustrating the proximity of adverse impacts on our ecosystem and human health during its whole life-time. This depth investigation would be helpful to understand the possible sources of emissions and discharges, potential impacts along with requisite measures and regulations for designing a sustainable 'T-Shirt' or a textile commodity.

Keywords: *textile commodity, impacts, LCA, green product, T-shirt*

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1. Introduction

LCA is an analytical framework used to assess environmental loads of a product from its cradle-to-grave [1]. Further, it acts as an evaluating form of chain analysis for different resources utilization such as energy, water and land through the structural pathways of the economic system with connecting to environmental impacts [2]. Textile sector is leading to 7% of international trade, providing jobs to 26 million in which most of them are women in Asian developing countries [3]. Textile commodities are mostly made from cellulosic materials i.e., polyester or cotton [4] and leading to flow of 3.2 million tons (MTs) of raw materials in which 0.9 MT are exported, 1.8 MT are sent to dispose at landfill and rest of 0.6 MT either recycled or incinerated [5]. As the clothing or textile commodities are incredibly important and intertwined with our daily life, the aim of this essay has set up to evaluate a 'T-Shirt' in context to 'green product' perspective of view. Generally 'T-Shirt' is made from cotton and associated with some other different production and consumption stages. Here, the quantitative evaluating tool LCA is used to assess the overall environmental effects of a 'T-Shirt', processes involved during production, and manufacturing, packaging, transporting, recycling or final disposal in context to its whole lifetime [1]. A 'triple bottom line' technique was suggested by ReferenceAllwood, J.M., et al. [5] which is composed of socio-economic and environmental impacts to assess the LCA of a cotton product to understand its Ecological Footprint (EF) to the surroundings during the whole to measure its sustainability. Ecological Footprint illustrates the balance sheet of human economic and resource utilization activities within regenerative capacity of that certain biosphere [6]. Besides, The Life Cycle Inventory (LCI) and LC impact Assessment (LCIA) consider as the sister tools of LCA also used to understand the total amount of utilized resources such as land, water and energy and emissions from different stages of a representative product to evaluate the adverse impacts human, natural balance of ecosystem for ecological sustainability. The economic activities are linked to environmental resources depletion and destruction of our ecosystems. LCA analyzes the inputs-outputs, material flow and emissions into the environmental system and also work as a tool for providing suggestions to the producer, consumer, policy makers and researchers to develop the sustainable environment friendly product design along with reduce, reuse, recover, recycle or final disposal techniques [2]. Furthermore, The Environmental Impact Index (EI), Life Cycle Costing (LCC) and Ecological Sustainability Index (ESI) based on scoring system also used to evaluate the sustainability of a cotton product [7].

The aim of this paper is to evaluate compatibility of existing acquainted green textile commodities by assessing their potential socio-economic, environmental and human health impacts through the most competent analytical framework LCA. Here, the most common textile commodity 'T-Shirt' has taken to scrutinize by differentiating its different life stages during whole life-span. This depth analysis-based study is consistent to green or clean product development goals that could be appeared as a contributory support in understanding the prospects and constraints for designing a sustainable green textile product as well will play a conducive tool for making decision for its sustainable design.

2. Life Cycle Assessment (LCA) of a 'T-Shirt'

The ecological footprint demonstrates the intervention of a product or an object on the natural environment and ecosystem as well socio-economic and health impacts that can be elucidated by the LCA [6,8,9]. This study speculated 'T-Shirt' manufacturing from its raw materials to final fate with classifying different individual but intertwined and interlinked phases those probably have a footprint on energy and natural resources.

2.1. Production Phase

Starting from the 'cotton production' as the raw material of a 'T-Shirt', there are different socio-economic and environmental impacts could be observed in associate with during its agricultural practices. Cotton production needs water, land, energy and potential nutrients. Reference [10] found that fertilizer application has the 33%, ginning 25%, irrigation 19% and field fuel use 17% of environmental impacts for cotton production as well as Green House Gas (GHG) potential and ecotoxicity. As a result, questions about sustainability is raised and challenged due to probability of multifaceted utilization linkage and adverse impacts [11]. Water as an indicator, is extensively needed for cotton production. Reference [12] stated that 3.14% of total global water footprint accounts for cotton production. The cotton cultivation needs irrigation especially in the dried regions. Consequently, construction of irrigation channel, dam or sources of water could be taken into account for LCA in order to being potential impacts on terrestrial and aquatic biodiversity as well as their ecosystems. The excessive irrigation from surface water could alter the hydro-morphological characteristics, contamination and transportation of pollutants and affect the human health. Besides, ground water withdrawal could lead to lowering the water table, contamination of heavy metals along with damaging soil texture, creating soil hole those could cause for landslide, earthquake or intrusion of pollutants into ecosystems and damaging natural resources. Land use assessment for cotton production shows the potential impacts on biodiversity including both flora and fauna and their ecosystem [13]. In this perspective, soil pattern, soil texture and moisture content, soil organic and inorganic composition, soil pH, salinity, nutrients such as P, K, N, S and the soil organisms could be taken as the indicator to evaluate the land use impacts [14]. The soil surface layer is also taken into account for assessing transformation status. The potential impacts from land use are reflected during the ginning, carding and combing process. The use of power-tiller for ploughing, use of mechanical tools for planting and harvesting have the probability to increase the soil erosion and damaging ecosystems of other vascular plants [15].

Applying 'energy use' indicator during cotton production also reflects the potential impacts to the biotic and abiotic environment. Energy is needed for running tractor and water-pump during ploughing and irrigation. Generally, tractor or power-tiller is run by fossil fuels i.e., hydrocarbon products those have the adverse impacts on soil ecosystem as well as potential threats to human health [16]. The combustion of fossil fuels emit the CO_2 that has the potential contribution to the global warming [17]. In addition, burning fossil fuel also emit some other gases such as SO_2, NO_x etc cause for acid rain. As well, it causes the cancer, damage of reproductive systems, stomach and alteration in anatomical features to the human as well as animals [18]. Besides, destroy the soil hydrophobicity and inhibit the total water and soil transport systems [19] cause the plant root toxicity and also affects the metabolic systems of soil organisms such as bacteria, fungi, bacteria, algae [17]. Furthermore, the biomass produce from the cotton tree has the potential to green house gas such as CH_4 emission. On the other hand, water-pump is run by electricity. In that case, source of electricity will make question for sustainability of the 'T-Shirt'. If the electricity produces from renewable sources such as solar, wind, geothermal, wave, hydro or biomass sources could be considered as the clean energy. Although some recent studies argued to consider the LCA of these cleaner technologies i.e., PV solar panel, wind turbine and other mechanical tools use in clean energy generation. Further, if the electricity is grid connected then the impacts could be calculated on the basis of proportion contribution of renewable sources of total electricity generation [2].

Availability of soil nutrients plays an important role on cotton production and affects the environmental parameters. Insufficient soil nutrients are lead to use of fertilizer. The applied nitrogen fertilizer emits green house gas N_2O to the atmosphere through the field emission or leached from plant's root by heavy rains. Intensive energy is needed during its production process where sources of energy are also required importantly to examine. Its field application has the potential impacts on Global Warming (GW), Ozone Depletion (OD), Acid Rain (AR), Eutrophication, Acidification, anoxic zone and bioaccumulation [15]. The leaching excessive N moves down to the ground water contamination to form nitrate that commonly in taking by human during drinking water and affected blue baby syndrome [20]. Besides, the applied pesticides and herbicides during the cotton production have adverse effects on environment, ecosystem and human health. Soil contamination by pesticides alters the microbial activities, kill beneficial insects; water contamination leads the disruption of aquatic ecosystems and bioaccumulation in food chain [21].

2.2. Industrial Phase

There is an intensive water and energy footprint of the 'T-Shirt' during the industrial processing and manufacturing stages. Both water and energy are needed for processing raw material from wool to pulp along with knitting, dying, washing, laundry, and woven drying etc. of textile fibers and finish product of the 'T-Shirt' [10]. These footprints could be obtained from analyzing the relevant all processing and manufacturing industrial processes. If we start first the 'bale opening-spinning' process that needs energy and water for mechanical operation, opening pulp, cleaning, mixing, carding, pre-drawing and drawing, combing and spinning cotton into yarn. Then the next 'yarn dyeing' process is compiled by the use of use of energy, bleaching, dyes and chemicals, scouring, dyeing, extraction and drying and yarn to colored yarn. Staging, jet preparation and dying with softening and drying are accomplished in the 'Batch dying' process. 'Knitting & Compaction' needs energy for knitting yarn to fabric and compacting to reduce length. Energy and chemicals also needed for beaming, drying, slashing, weaving, warping and filling yarn into fabric. 'Continues dying' process takes time and use relatively more water and energy for singeing, desizing, mercerizing, scouring, bleaching, dying, drying and re-drying of yarn into colored yarn and prepare for 'Sanforizing' process to shrinkage the finished fabric. Finally, 'Finishing' used to wet finishing, drying and curing fabric [15].

Reference [22] reported that wood-based fiber needs $20m^3$ water during processing and 243 m^3 for cooling of per metric tons fibers. According to Wang, J., et al. [23], dying industry is ranked in second position for water consumption within all industries that consumed 9.548 billion tons in 2010. Simultaneously, this industry annually consumes significant amount 68.67 million tons of standard coal equivalent energy [24]. Energy is required for almost all mechanical operation, spinning, knitting, washing, dyeing, drying and finishing. Reference [25] stated that almost 50% electricity consumed during the spinning process. Using gasoline for heating to produce high temperature emits extensive amounts of SO_2 and NO_x. Energy also requires for effluent treatment during the aeration with blowers, agitation and different motors for whole treatment process [26].

The used dyes and chemicals such as Sodium sulphate (Na_2SO_4), Soda ash (Na_2CO_3), Caustic soda (NaOH), Reactive Black 5, NaCl are highly polluting compounds to the surrounding environment especially on soil and aquatic body [25]. These chemicals become contaminated with water and indicate the pH value of water. The untreated metal and dyes effluents greatly influence on Biological Oxygen Demand (BOD), Dissolved Oxygen (DO), Chemical Oxygen Demand (COD), Temperature and Volatile Organic Compounds (VOC) those severely inhibit the metabolic activities in aquatic environment [27]. The contaminated hot dyeing water (approximately 130^0C) instantly kills the aquatic organisms. These polluted effluents also affect the soil environment by the surface runoff. The soil contamination leads to adverse effects the soil organisms. Human beings are also vulnerable to the wastewater pollution. They affected by both chronic and acute effects due to up take aquatic organisms such as fish bear the toxic metal ions through the bioaccumulation and biomagnifications. Further, contaminated with groundwater by leaching through soil and accumulate into the human body during drinking the drinking water. The most notable chronic symptoms such as cognitive e.g., poor judgment, concentration and memory, anxiety, worry etc. emotional e.g., irritability, loneliness, depression agitation etc. physical e.g., aches, chest pain, nausea, dizziness, diarrhea etc and behavioral e.g., deteriorating nervous system, aggressiveness, silence etc. Besides, acute effects are damaging kidneys, nervous, cardiovascular, reproductive, endocrine and suppression immune systems, cause cancer and tumors, damage or alter DNA etc [28].

These industrial processes also have the potential impacts on the atmospheric environment and affect directly and indirectly the all spheres i.e., biosphere, lithosphere, atmosphere of our environment. If we use environmental impact indicators upon the emitting gases and discharging effluents from these processes reflect that CO_2 has the GW potential, SO_2 has acidification, PO_4^- and NO_3^- have the eutrophication, CH_4 contribute to GW, C_2H_4 photochemical oxidant formation and R-11 (CCl_3F) has the ozone depletion potential [25]. The amount of energy consumption and emission potential both are high in the stentering, setting and effluent treatment processes and ecotoxicity level is also high due to discharging huge amount metals [26]. Reference [29] noticed that the application of bleach and enzyme for a 'T-Shirt' from scouring to bio-polishing or enzymatic rinse process (ERP) produces organochlorines, persistent pollutants and dioxin gas all of those have adverse impacts on natural aquatic and soil environment also causing human carcinogenic and respiratory problems.

Packaging is a major source of environmental burden, waste generation and also important for storage and transportation for optimizing quality [30]. Reference [31] found the one-third of total environmental impacts is raised during the production and transportation of packaging of total product life cycle. The used raw materials in packaging system affect the sustainability of the product through increasing reuse or recycling or reducing the weight of generated waste [1]. The fuel types of vehicles used for transporting finished 'T-Shirt' are also a considerable indicator to assess the sustainability. The automobiles have the potential to noise pollution that affect the human health. Besides, automobile washing water is contaminated with petroleum and detergent cause the water pollution and eutrophication. The fossil fuel burning and air conditioning in automobiles have the GW and OD potential for emitting green house gas CO_2 and CFC. The toxic CO, NOx, hydrocarbon, particles and metals are also released during the emission. The scrapes from automobiles have now also considered as global environmental problem for its high management cost.

2.3. Consumer Phase

The distribution process of 'T-Shirt' in the market also can raise the question against it as a green product. The supplied energy sources to shopping mall and supermarket represent the ecological footprint on the basis of proportion of grid connected electricity. In the consumer phase of a 'T-Shirt' generally runs until its end of life. During the consumer phase it has footprint on water and energy. It needs water to wash and electricity for ironing. Inc., C. [15] reported a knit shirt is washed almost 56 times in its whole cycle although laundering behavior significantly influences it. The 'T-Shirt' considered as 'waste' which is based on the user preference.

2.4. Recycling Phase

Globally there are many millions of tons textile wastes are generating every year. A significant proportion of these textile products are needed to recycle. The main sources are processing and manufacturing, domestic furnishing, wearing etc. According to EPA (2011) there are 2 millions of clothing waste recovered from its postconsumer (individuals) and pre-consumer (manufacturer) in US. WRAP [32] mentioned that every year 31% of clothing wastes are sent to landfill for final dumping which are equivalent to 350,000 tons of used is clothing in UK. European Commission (EU) reported that there are 5.8 MTs produce by EU consumers in which 25% recycled by charities and rest of 4.3 MTs are disposed in landfill or burnt [33]. Land filling of Clothing materials has different detrimental effects on environment and soil ecosystem [7]. Methane (CH_4) and CO_2 are the major GHGs emitted by decomposing clothing materials at the landfill those have the GW potential. The used dyes and chemicals used in fabric have the proximity to be contaminated with the soil, surface and groundwater by leaching. Incineration the most prominent another types clothing waste treatment process also emit furan and dioxin gases, SO_2, HCl, fine particles etc. The residual flying ash is contaminated with different sorts of heavy metals such as Mercury (Hg), Lead (Pb), Cadmium (Cd) etc. These gases and metals have the GW, Acidification, Eco-toxicological potential to the physical and human environment. Besides, the incineration process also needs energy for burning wastes by high temperature.

Besides, gender and poor-rich discrimination, child labor, low wage, power relation with its supply chain and priority to power full people for supply can raise question for achieving sustainability. For example, Asian cotton production sector is not gender neutral. The gender ideologies in this region made women as “docile, nimble and unskilled” which push them to be assigned to the informal sectors [34].

3. Prospects of Sustainable ‘T-Shirt’ Design

A sustainable product means no ecological footprint or deficit to the natural environment during its whole life-span [6,8]. Generally it does not emit harmful gases, use less or zero or clean energy, not produced by social discrimination e.g., neglecting oppressed people, considered caste in production, get preference for resource utilization, not genetically modified, try to best reuse, reduce, recycle, recovery and sustainable disposal management.

The LCA of a T-Shirt and probable sources of emissions in Figure 1 are illustrating the holistic view for designing sustainable T-Shirt. If we look at the different phases, we will find the water, energy, chemicals, land and labor as the main indicators for evaluating the sustainability of a T-Shirt. In essence, we can reduce or abate the ecological footprint by efficient and sensible use of these resources. Cotton contributes almost 0.8% of CO_2 of global total in its whole life-time [35]. As we see, irrigation is the major source of global water use [36]. The water used and energy requirement in cotton production phase is relatively lower than other phases of entire life of ‘T-Shirt’ consequently leads to low ecological footprint [15]. Contrary although global cotton producing arable land covers only 2.4% but accounts for total 11% of pesticides in every year [37]. [1] conducted a comparative LCA between conventional, organic and Genetically Modified (GM) agricultural practices and found organic one requires less fertilizer and pesticides consequently less environmental loads though needs more arable land. Similarly, GM species help to reduce field emissions by lower herbicides application, water use and other field operation systems.

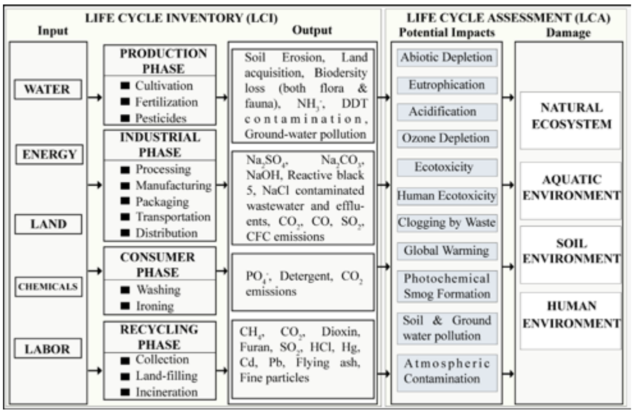

Figure 1. Sustainability assessment of a ‘T-Shirt’ by using LCA framework

Efficient or alternative use of chemicals to reduce contamination as well as maximum treatment initiative could potentially reduce adverse impacts of discharged effluents and emitted gases. Reference [26] reported that industrial processes are needed to take into consideration for designing cleaner products. Almost all processing and manufacturing stages consume a lot of water and energy that leads to emit different sort of gases (CO_2, SO_2, CFC) along with discharging wastewater and effluents (PO_4^-, NH_4^-,) both have major potential impacts on acidification, eutrophication, ecotoxicity, resource scarcity, health impacts etc. Most of the literature suggested that improving and altering technical processes and raw materials in textile industry could significantly contribute to reduce these impacts. For example, sewing has lowest GW and eutrophication potential than the desizing, scouring and bleaching due to relatively low COD emissions and also landfill is more effective than the incineration for these discharges. Further, reference [23] reported that dyeing probably responsible for more environmental impacts for generating huge amount of highly contaminated wastewater and avoided by industries for high treatment cost (only 7% was treated in 2010). Besides, energy use during production, processing, marketing, transporting and washing of ‘T-Shirt’ are the prominent sources of energy and emissions.

Considering renewable energy sources from cradle to grave could minimize or abate the emissions. Globally solar water pumping system is encouraged by energy and environmental expert because of its cost effectiveness for irrigation. According to HWWI [38] report, India has the potentiality to save at least 225 billion 1tr/year of diesel by using ‘Solar Photovoltaic (SPV)’ systems in the irrigation sector. Industrial processing and manufacturing phases also have great potentials to reduce impacts as like. Reference [39] reported that renewable energy will contribute 21% of total industrial use in 2050 that would be equivalent to 50 exajoules in a year (EJ/yr). Consequently, potentially contribute to abate 10% of total and 25% of industrial GHG emissions. In addition, energy efficiency also make a remarkable constitutes along with it. For example, reference [2] found that efficient energy use during packaging materials, types of preservation and consumption behavior leads to energy saving. It has the potentiality to abate 15-20% of total CO_2 emission reductions in industrial sectors [39].

The deal with end-product i.e., reuses, recycle and recover of 'T-Shirt' waste also importantly considered for being sustainable. According to reference [25] Recyclability Potential Index (RPI) could be used to quantify the economic and environmental benefits from the recycled materials of a textile commodity. The highest RPI value indicates the more gains from recycling process BS brings enormous benefits to us [40]. It helps to conserve resources (water and energy), minimize impacts (ecological, carbon footprint and health effects). Cotton waste has multiuse potentiality. It could be used in pulp and paper industry for producing paper, bond, medically for bandage and pulp and cellulose production for chemical industries. Also shredded used for mattress, quilt in bedding and yarn for spinning industry. It has a great energy value, mixing with cow and pig dung generates biogas and unusable portion could be burn to produce thermal energy. Moreover, current research found it as an excellent bulking ingredient with rich of protein (7%) for lactating cow. Further, its high water holding capacity, good C-N ratio and low heavy metal content recommend to land application as a compost as well as alternative of fertilizer.

The responsibility for ensuring sustainable work environment is reflecting from all most sides i.e., producers, consumer, buyer, government, non-governmental agencies. The ongoing global competition for cleaner and lower price, women work environment and wage has increased to the satisfactory level for some countries [41,42].

4. Conclusions

Nowadays, 'sustainability' is using as an important tool for branding, pricing, attracting consumers, considering preference for a cotton product development. LCA is a prominent tool to assess the environmental footprint of a 'T-Shirt' production from raw material acquisition through consumer use and disposal. Different sorts of sister tools of LCA such as LCI, LCC, EI, LCIA, ESI and RPI are used to see the socio-economic and environmental impacts of a 'T-Shirt'. This assessment is eliciting that every stages of a 'T-Shirt' production from raw materials to disposal phase have proximity to discharge hazardous effluents and emissions of gases. Consequently, has the potentiality to affect our socio-economic condition, all spheres of environment and health through GW, acidification, ozone depletion, acid rain, eutrophication, surface and ground water and soil contamination all of those lead to acute and chronic effects on human health.

Use of LCA as a decision support tool, suggest the dos and don'ts for producing a sustainable 'T-Shirt'. The illustrated reasons of footprint are suggesting for saving potential resources such as water, land and energy. The renewable energy sources could minimize the existing equivalent production cost and abate the damage cost. Further, prioritization of user habit on the basis of cost-benefit analysis (CBA) could be a guild line for more user-centric sustainable product design. Efficient resources utilization, ensuring maximum use, rethinking for alternative of hazardous materials and reuse, recycle; recover before final disposal would be an effective effort a sustainable 'T-Shirt'. In addition, legitimacy would be another important one to monitor the use of pesticides, toxics, to aware people, emphasize clean production, training, financial assistance or subsidize in manufacturing level and advocacy program could play vital roles.

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