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Review

Sustainable management of textile and clothing

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Abstract: Textile and clothing industry (T&C) is the second largest industry in the manufacturing sector. Currently, the industry operates on a linear model. Its value-chain is associated with several problems such as environment pollution (solid wastes, effluent discharges, air pollution, and emission of greenhouse gases), and resources extraction and depletion (raw materials, water, energy). These problems present the challenges that are addressed in this paper. These problems are further exacerbated by the rapid growth in population and attendant need for economic growth. There is therefore need to begin to address how to make the industry more sustainable. This will entail reviewing the entire T&C value chain from raw material extraction to post-consumption of its products. Nigeria, an emerging economy is used as a proxy for the study. The management of textile/clothing wastes in Nigeria does not follow best practices, as the wastes are generally, disposed at dumpsites. Even though Nigeria is rich in natural resources to produce textiles, the country largely depends on importation of finished T&C goods. This paper uses three models namely: new business model, efficient waste management system, and regenerative production processes and materials to demonstrate how the industry can become more sustainable. This effort will focus on reuse and recycling of textile and clothing products. Emphasis is built on eco-design to encourage proper waste management system to support recovery, reprocessing, reuse, and recycling of textile and clothing products.

Keywords: textiles; clothing; circular economy; sustainability; resource efficiency; Nigeria

Abbreviations: T&C: textile and clothing; CE: circular economy; EOL: end-of-life; MSW: municipal solid waste

1. Introduction

Textile and clothing (T&C) industry is the second largest polluting industry, after oil in the world. It employs an estimated 60 million people worldwide and accounts for more than $450 billion in revenues annually [1,2]. Its products are very vast but clothing makes up 60% of the entire T&C market [3]. Production, supply and use of textile products require and consume huge amount of non-renewable resources [3–8]. There is also rapid proliferation of textile products and this has shortened the life span of the products. For example, the number of times a cloth is worn before being disposed has reduced significantly by 36% [3,5,9]. This phenomenon has given rise to "fast fashion". Fast fashion means readily available and cheaply made fashion. Prices are maintained low by outsourcing production to low and middle-income countries (LMIC) [9]. Global consumption of textile in 2015 was about 95.6 million tons [10]. The environmental concerns include the use of energy, water and hazardous compounds, carbon dioxide emissions and solid waste generation. T&C industry is the second highest consumer of water globally [11]. About 93 billion cubic meters of water are used by the industry annually. Its water consumption represents about 4% of annual freshwater withdrawal [12]. In addition, 200 liters of water is required to produce 1 kg of fabric. The water is used to wash the fiber, bleach, dye and clean the finished product. Most often, the wastewaters are not re-processed before they are released to the environment. They therefore, further pollute the underground water supply. The production process also contributes to air pollution. Considerable amount of solid waste is generated by the industry [10].

It is estimated that by 2050, clothing sales will triple from today's level [11]. The increased demand is motivated mainly by rising markets in Asia and Africa [5,12–14]. These have serious ecological implications. For example, out of 72 million tons of PET produced globally in 2015, 48 million tons (66%) were amorphous PET used for fiber production (polyester) [15]. Annually, washing of clothes discharges 500,000 tons of plastic micro-fibers into the ocean. This is the same as 50 billion plastic bottles. Most of these fibers are polyester, which are contained in about 60% of cloths. Production of polyester emits 2–3 times more carbon than cotton. Further, polyester does not degrade in the oceans. An IUCN (International Union for Conservation of Nature) report projected that 35% of micro-plastics in the ocean are related to washing of synthetic textiles like polyester [11]. Globally, cotton production uses 2.5% of agricultural land, and consumes about 16% of pesticides. It also accounts for 4% of NPK fertilizer usage. The runoffs cause water pollution, thus leading to eutrophication [16,17]. Wastewater from textile plants are mostly untreated, and contains elevated amounts of pollutants that are discharged daily to water bodies [10]. Wet processes—dyeing, printing and finishing—uses a large amount of chemicals and water. Estimate shows production of 12–20 tonnes of textiles produces about 1000–3000 m^3 of waste water. The use of boilers, ovens and storage tanks are the three major causes of air pollution in the T&C industry. The drying process, which requires high temperature, produces emissions. Gases are also released during dyeing process [18]. The industry accounts for about 10% of global emission of carbon dioxide [2]. Table 1 was adapted from [5] and shows the ecological implications of T&C product lifecycle.

Table 1. Ecological Implications of products (including textile) lifecycle processes.

Environmental footprint	Processes
Energy use	Production of synthesized fibers, yarn manufacturing finishing processes. Consumers: Washing, tumble drying, ironing.
Water and chemicals consumption	Fertilizers and insecticides for cotton and fiber growth, wet pre-treatment, dyeing, finishing and laundry. Consumers: Water for washing, detergents and other laundry chemicals.
Solid and liquid waste	Dyeing, bleaching, printing and finishing releases effluents and solvents. Textile/clothing production associated solid wastes (off cuts). Plastic microfibers, Distribution wastes—packaging, tags, bags, etc. Consumers: Disposal of used clothing items, non-biodegradable polyester, microfibers.
Direct CO_2 emissions	Emissions from energy use for production. Transportation within globally dispersed supply chains. Incineration of end-of-life clothing.

Note: Source: Adapted from [5].

About 1,900 different chemicals are utilized in the production of T&C. 165 of the chemicals are categorized "chemicals of concern", unsafe and harmful to health and the environment [13]. Textile dyestuffs include huge quantity of organic compounds, which are not easily degradable and are resistant to aerobic degradation. Under anaerobic state, they are reduced to carcinogenic agents [18,19]. Trace amounts of heavy metals such as lead, nickel, copper, chromium are found in dye effluents. Other pollutants are carboxyl methylcellulose (CMC), polyvinyl alcohol, sodium hypochlorite, sodium hydroxide, acids, surfactants, Na_2SiO_3, sodium phosphate, dissolved solids, oils and alkaline [20].

The clothing (garment) industry is also associated with other health, social and labour disasters. This includes child labour, sweatshop labour, and very poor wages for workers. The workers usually work in unsafe and hazardous environments especially in developing countries. Examples include the collapse of Rana Plaza factory in 2013, which resulted to 1,134 deaths of Bangladeshi workers; the Tazreen factory fire of Dhaka, November 2012, that killed 112 workers [21,22].

In Nigeria, textile waste is part of the solid wastes generated. For example, in the capital city Abuja, fabrics account for between 1.42–1.6% of wastes generated by households [23,24]. Other major cities like Ibadan and Lagos have reported 3.67–4.97% and 1.6–5.4%, respectively [26]. Others were reported by [27–30]. Nationally, textiles accounts for 2.48% of total municipal solid wastes [29].

Since there is no available textile recycling facility in the country, it will be useful to explore various sustainable management practices to address T&C waste management in Nigeria. The paper therefore, explores the use of circular economy in the T&C industry. The first section of the paper gives general background, and an overview of ecological footprint of T&C industry. The second section reviews the concept of circular economy and textile waste recycling. The third section reviews the

characteristics of the study area. In the final section, we provide policy and legislative framework, and effective waste management system.

2. Sustainable approach in T&C value-chain: circular economy

Linear economy (LE) developed immediately after industrial revolution. It encourages waste instead of supporting regenerative economy [26,31]. For example, incorporating 12% recycled content in denim textile consumes 9.8% less water; 4.2% less energy and 3.8% CO_2 emission.

Landfilling of textile waste also has economic implications. For example, it costs the UK economy about $108 million annually to landfill domestic textiles and cloths [31]. Circular economy (CE) encourages reuse and recycling of products from inception. This practice extends the life of a product and its components while minimizing the use of nonrenewable and non-replenishable materials through a product's life cycle [32]. Ellen MacArthur Foundation [33] presents the Rs of CE to delineate the different functions and stages in circular economy. The three major stages are smarter product use and manufacture (Refuse, Rethink, Reduce); extend lifespan of product and its parts (*Reuse, Repair, Refurbish, Remanufacture*); and useful application of materials (*Repurpose, Recycle and Recover*). Some of these concepts may be difficult to apply in the textile and clothing area. However, they could still extend the useful life of the clothing material. For example, textile materials may be repaired and can be refurbished. By creating alternative markets and use for these products, the life cycle can be extended.

To achieve circular economy in the T&C industry, four critical steps must be followed [12]. They are: (i) Phase out unsafe materials and microfiber discharges. This requires innovative design and production processes; (ii) Change the ways cloths are designed, marketed and used; (iii) Design product for recycling by using products that are recoverable; and (iv) Build efficient utilization of resources and shift to the use of renewable materials [12]. These require a substantial change in product designs and consumer behavior to encourage sustainable practices.

There are three main categories of textile wastes: post-industrial wastes, pre-consumer wastes and post-consumers' wastes [34]. Post-industrial and pre-consumer wastes are classified as production wastes [3]. Post-industrial and pre-consumer wastes include wastes generated from natural and synthetic fibers production, spinning, weaving, knitting, dyeing, printing, finishing, designing, and cutting, wholesalers, trading companies, retailers and mass merchandise chains [35].

Some brands and vendors have begun to attend to certain ecological or societal issues in their value-chain. For example, Archroma has produced "Earthcolours"—range of colours of dyes made from agricultural residues [36]. Beyond Surface Technologies has also developed resilient water repellant that does not use PFCs [37].

Efforts to decrease ecological impacts may lead to higher cost of items for consumers. Influencing buyers to purchase fewer clothes or to extend the number of times a cloth is worn (slow fashion) will lower profit margins. Accordingly, most recommendations include discovering a more sustainable fabric blend to decrease the utilization of traditional cotton; advancement of technologies for sorting and reprocessing; development of a more efficient washing and drying processes; and improved energy efficiency and use of renewable energy throughout the T&C lifecycle [13].

The three methods to manage end-of-life products are regulation-based [31,38,39], free-market based [2,9,40] and taxation based [12,31].

2.1. Ways in which textile waste can be reprocessed

Proper management of solid waste requires integration of waste hierarchy in management viz: *reduce, reuse, repair, recycle, recover* and *dispose.* This is also referred to as *prevention, minimization, reuse, recycling energy recovery* and *dispose.* Compared to recycling or energy recovery, reuse is a better alternative in the waste hierarchy. However, it is not always possible for every form of textiles [41]. Cloth and textiles are complex items because of their material composition. The choice of treatment depends on whether the materials have been separated. If they have not been sorted, or the materials are combined with non-textiles and are contaminated; they are more likely to be disposed to landfill, incinerated or recycled. Three factors increase the viability of T&C recycling [5]. They are: (i) product design, fiber composition, fabric finishes, production processes, accessories used, logos and emblems, durability (degree of wear) and manner of labeling; (ii) technological potential; and (iii) disposal methods—collection, sorting and grading. Figure 1 below, adapted from [3] shows lifecycle of textile and clothing.

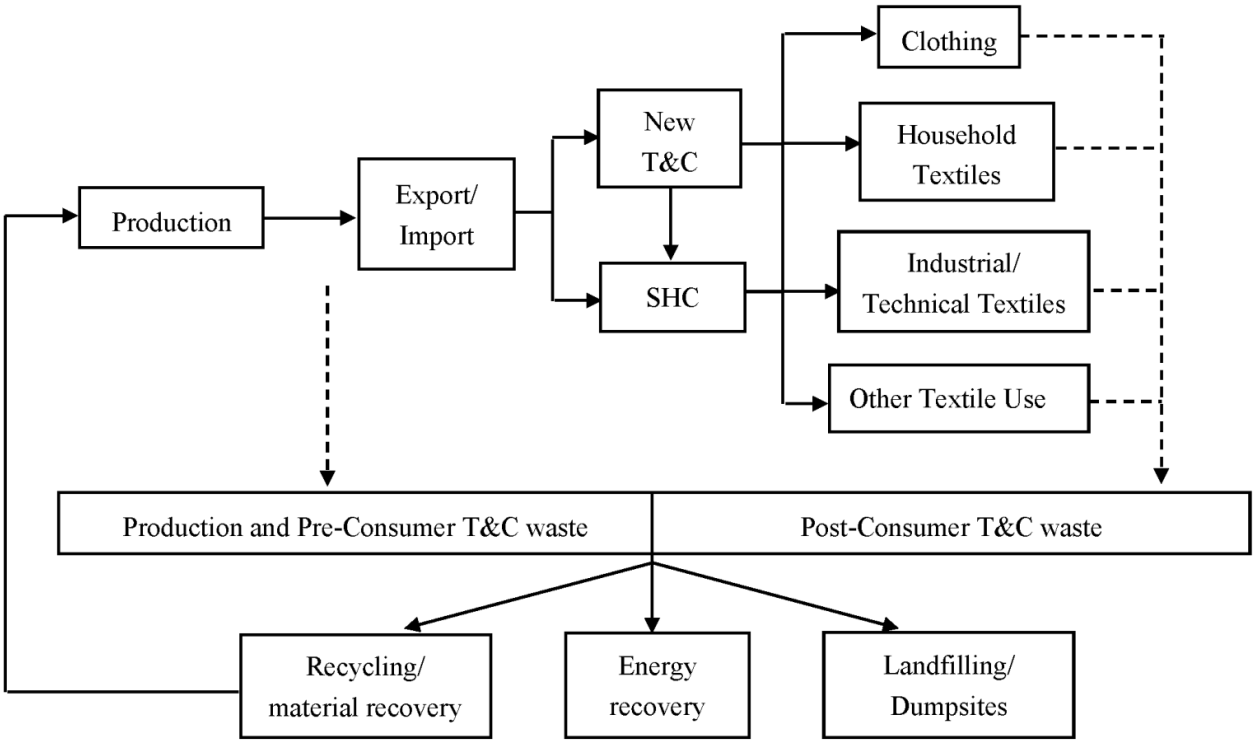

Figure 1. Lifecycle of textile and Clothing (adapted from [3]).

Barriers that have limited closing the loop (recycling) in T&C industry include: (i) consumer behavior and education; (ii) disposal methods and processes are lack of technical knowledge—how on efficient collection and sorting of textiles by the type of fiber; poor availability of facilities; and (iii) poor recycling technologies and high cost of recovery processes. In addition, the present business model of fast-fashion-militates against sustainable textile and clothing industry [5]. Generally, the methods of

managing used T&C include reuse, material recovery (textile recovery) and energy recovery. For example, the removal of flame retardants (FR) before use as agro and geo-textiles suggests the importance of lifecycle assessment in T&C. This includes sustainable design and material (fiber), recycling (upcycling and downcycling), reuse, energy recovery, etc [4]. Many examples of use of textiles (cotton) include cement-based composites for building construction; polypropylene reinforcement without further treatment; composites in automotive industries, biogas through anaerobic digestion, bio-methane; gasification for heat, power and biochar co-production, bio-oil through pyrolysis, etc [8,42,43].

2.1.1. Reuse

A common way to reuse textile is to market them as second hand clothes (SHC) or donate them to charitable organization. Apart from the charitable donations, huge amounts of the used clothes are usually marketed in many of the developing countries of Africa, Asia and Eastern Europe. In 2008, about 26,000 tonnes of used textiles were collected by charity organizations, with the sole purpose of donating them to Africa and Eastern Europe [41]. Though trade in SHC has its undesirable effect: "environmental injustice" [9], argues that the ecological benefits include savings on energy and cutting down on emissions and demands for virgin materials [41]. However, preferred alternative of end-of-life textile management is re-using the waste material by re-integrating it directly into the production process to reduce material consumption [3]. Irrespective of how many times a T&C is reused, it must eventually reach its end-of-life (EOL), and will be discarded. Thus, there is need for sustainable materials design and improved methods of recycling textile products.

2.1.2. Material recovery (textiles recycling)

Recycling is prominent in ensuring the reuse of material components of a product. There are two forms of recycling: "open loop" and "closed loop". In open-loop recycling, textile cascade to lower value utilization because of reduced quality, while close-loop recycling maintains materials in the unchanged product value chain (e.g. fiber-to-fiber) [15]. Though lack of technical innovation and availability of cheap fabrics in market limits the interest in adopting recycling practice; technologies for reprocessing textile waste are growing [3,12,13,41]. Different fibers and diverse colours of textiles are constraining issues in textile recycling. They hinder the sorting processes and reduce the feature of reprocessed materials.

The different textile reprocessing methods include mechanical, chemical and separation using N-methylmorpholine-N-oxide (NMMO) [3,15,41,44].

2.1.3. Energy recovery

Relative to other 34 feedstock such as polyester, etc, cotton has high cellulose content (85–95% dry wt.). It is therefore highly viable for conversion to bio-fuels. Though the development is still in its infant stage, the use of the solvent N-methylmorpholine-N-oxide (NMMO) in pretreatment of cotton/polyester blend produces methane. The use of NMMO in treating jeans which is 100% cotton, produces 400ml methane/g volatile solids/day. A major benefit with the NMMO is that it can be reused. The NMMO

processes require less energy, is easy to operate and is environmentally friendly. It can be applied to all cellulose material, viscose, etc [45–47]. Also, thermal treatment of waste textile generates heat energy. It does not require separation. For example, in Sweden, a combined heat and power plant (CHP) using the combustion technology fluidized bed was used to produce energy. However, the method has its difficulties. Optimal results can be obtained when the textiles are mixed with cardboard to obtain uniform burning [45].

2.2. Limitations of recycling/reuse

Every product reaches at a certain point in time its end-of-life, thus the criticality of recycling and/or reuse. For example, polymer, oligomer and monomer fabric/fiber are difficult to sort and separate into pure fractions because of lack of technology. Further, fabric and fiber recycling generally produces materials of lower quality, except when they are blended with yarn from virgin fibers. Most recycling effort is to use lesser virgin materials and not really to use only post-consumed items. Therefore, recycling sometimes results to "down cycling" (in terms of quality, suitability for purpose and aesthetics). There are also many non-technical challenges for increased recycling of textile. Additionally, some of the advantages offered by textile recycling may be offset by increased consumption (a rebound effect) [44]. Textile recycling may also introduce other ecological problems if for example, it depends on the use of fossil energy or other limited natural resources. Sometimes, ecological impacts may be transferred from one region to the other. For example, countries that are beneficiaries to the used cloth may bear the burden of disposal of the cloth at the end of their useful life. Thus, they may end up in the landfill of such countries. It is essential that a thorough lifecycle assessment be conducted to review the benefits of such practices and take the best action [44,48,49].

3. The study area

Nigeria is located in West Africa. National census conducted in 2006 recorded the population of the country as 140,431,790. With projected growth of 2.7% per annum, population of Nigeria is estimated at above 198.6 million. Nigeria is seventh most populous country, accounting for about 2.6% of world population. Nigeria has a very young population, with national average of 18 years [31,50]. Youths, are one of the main driver of fast fashion and fashion in general [12]. With the growing population, economic growth and expanding middle class, it is expected that clothing market will continue to grow in Nigeria. The country is a lower middle-income economy and is classified among African countries with GDP per capita of between $786 and $3,115 in 2013 [51].

Although the volume of waste produced has increased in mass and composition, there is no corresponding expansion in provision of solid waste management system. Where functional, it is very poor. Poor waste management is one of the major environmental challenges affecting Nigeria. Wastes are carelessly disposed to water bodies, open spaces, across roads, drainages, etc. Nigeria produces about 32 million tons of waste every year. Lagos State generates waste of about 16,500 tons per day corresponding to 825 trucks of 20 tons each day [30]. Most of the wastes are largely dumped in dumpsites, which are not engineered or have leachate control. 70% of the country's wastes are organic, while 30% are non-organic wastes [52]. Only about 28% of the wastes produced in Nigeria can be recycled. In Abuja, the capital city, it is more than 40%. Poor and infrequent collections of wastes are

largely due to lack of funding. Collection and transportation of wastes are capital and labour intensive, accounting between 70–80% of Nigeria's overall cost of waste management [53]. Organics accounts for the greater amount of the wastes in the country. The others include plastics, metals, textiles, etc [52,54]. General practice among Nigeria waste managers is to collect varied waste materials and deposit at dumpsites without segregation, especially since segregation is not done from source [31]. Table 2 conceptualizes sustainable management of wastes across the T&C value chain.

Table 2. Sustainable management across T&C value chain.

Post-industrial	Pre-consumer	Post-consumer
Renewable or sustainable agriculture (cultivation) of plant fibers.	Rentals and subscription model.	Reuse, re-sale, donate.
Utilization of renewable energy in production and distribution.	High value re-sale business model.	Reduction of textile waste (and purchase of T&C).
Substitution and use of sustainable fiber and new production processes.	Reuse of recovered materials for new clothing design.	Source segregation of textile wastes.
Design clothes to be used more number of times - durability (or slow fashion).	Integrate recovery mechanism of T&C wastes in marketing strategy.	Dispose to collection agency for reuse, recycling and energy recovery.
Scaled return of used T&C through various instruments.	Promote recovery and collection of textile wastes.	Accelerated and viable collection, sorting, grading and recycling technologies and processes.
Technological advancement that scale the economics and value of recycling post-consumer T&C.	Cooperation with remanufacturing enterprises - Cascading (open-loop) or closed-loop of textiles wastes.	Education, awareness and sensitization.
Legislated and free-market sustainability in all processes.	Increased use of renewable energy in marketing and distribution network.	Financial, economic incentives.
Education, awareness and sensitization.		Effective policies/legislation towards proper waste management system for EOL products.

3.1. Future directions

Nigeria is expected to be the third most populous country by 2050, at 402 million people [55]. Assuming waste generation of 0.43 kg/capita/day [30], about 172,860,000 kg/day (172,860 tons/day) will be generated across the country by 2050. Assuming, textiles waste composition of 2.99% (for households) and 0.75% (for commercial and institutions) [52,54], we estimate that textile wastes will amount to 6,464,964 kg/day (6,465 tons/day), corresponding to 2,353,246,896 kg/year (2,353,260 tons/year) in 2050. Consequently, there are the need and urgency to chart a sustainable path for post-consumer products (T&C waste). The paper will not focus on the health and socioecological implications of T&C industry since Nigeria is not a major producer of clothes.

Considering the high demand for labour in collection, transportation, sorting, recycling, of used cloth and textile materials, transition to circular economy will invariably, contribute to the socio-economic growth of Nigeria. It will offer employment opportunities for the growing youth population in Nigeria. Circular economy may lead to the emergence of new industries with diversified business interests. To support circular economy, there will be need for infrastructure development—road, railways, power, etc. Beyond economic impacts, efficient CE system will help to change the negative perception of "wastes". The waste to wealth concept that may emerge may help to transform attitudes and behaviours that may promote clean and healthy environment.

3.1.1. Policy and legislative framework

The goal of any policy or legislative framework should be to recover and recycle all municipal waste. This includes technological, social and political support and legislation. Currently, legislated "circular economy" is in the infantry stage in Nigeria. For example, EU has several directives on circular management of many waste streams, tires, plastics, etc. Foremost of which is the European Waste Framework Directive (Directive 2008/98/EC) which established the fundamental characteristics associated with waste management, such as definition of waste, recycling, recovery [3]. The EU Circular economy package adopted in 2018, directed that textile "waste" should be collected differently. By the end of 2024, targets will be established for reuse and recycling of textile waste. Further, EU Landfill Directive calls for member states to decrease to 10% the portion of municipal waste entering landfill by 2035 [13]. Policies should therefore encourage the involvement of several stakeholders such as financial institutions, researchers, and other active participants in Nigeria. In Nigeria, the rate of recycling is very low [31]. Poor quality of recycled fibers because of "shorter fiber" is a continued challenge to the use of recycled fiber in production of new cloth. Therefore, recycling for reuse in cloth production may not at present, present business opportunities. Instead, the country should focus on recycling for industrial and other technical usages such as manufacturing of insulation materials and, mattresses. Policy directive should gear towards providing incentives such as tax rebates and waiver for businesses that invests in recycling and utilization of recovered materials in their production process.

In Nigeria, free market system may be a better approach to sustainable management of post-consumer T&C materials. EPR is currently in place. However, there are challenges, as smuggling of textiles through Nigeria's borders accounts for large presence of SHC and other textiles in the country. There are broad ranges of issues that may help to achieve sustainability in T&C in Nigeria. Specifically,

we classify those issues as follows: (i) new business model; (ii) sustainable fiber; (iii) efficient waste management system; and (iv) renewable energy.

3.1.2. New business model

Cooperation or partnership between the actors is important to build extensive transformation and surmount challenges such as uncoordinated standards. There is a need for transformation to new business model that will consider regional attributes, income levels and existing clothing use trend. For established markets such as Europe and North America, the major issue is to extend the useful life of textile products and reduce the early disposal of used clothes [12]. In countries like Nigeria, effort should be on a new business model that encourages alternative uses of textile materials through using, re-using, leasing and renting, etc.

Different business models for sustainable clothing consumption include [9,12]:

i. Short-term clothing rentals
ii. Slow fashion
iii. Subscription model
iv. Re-sale
v. Recycling – cascading (open-loop) or closed-loop

Nigeria is a major importer of SHC. Rentals of designer clothing especially for traditional and ceremonial events may help to prolong the life of such materials. Similarly, the re-sale market for high-end clothing used in Nigeria will be very substantial. Therefore, there may be a viable market opportunity for companies that will specialize in retailing high-end fashion (traditional and western clothing) used by affluent and upper middle-income Nigerians.

3.1.3. Sustainable fiber

Textiles are produced from many materials and are categorized according to their constituent fibers. They are: animal (wool, silk), plant (cotton, flax, jute), mineral (inorganic) fibers (asbestos, glass fiber), and synthetic (nylon, polyester, acrylic). In the past, all textiles were produced from natural fibers: plant, animal and mineral (inorganic). Currently, synthetic sources made from petroleum are the leading source of fibers [41,56,57]. Production of cotton and polyester is estimated to grow by 40% for years. Cotton now represents almost 33% of textile production worldwide, while synthetic fibers are about 60%. Other cellulose accounts for 4%, wool (2.1%) and flux (linen) 1%. It is estimated that an increase in demand of 84% within the next 20 years will stretch resource extraction to reach a breaking point [5,58]. Apart from new business model and slow fashion, a major approach that will curtail the ecological impact of textiles is the use of sustainable fiber.

Cellulose accounts for 99.5% of bamboo fiber, while ash and wax are 0.25% and 0.24%, respectively. Cellulose is essential to production of textile. Bamboo, grows in 23 states of Nigeria. The issue of "sustainability fiber" which is growing [9] portends a positive outcome for Nigeria. For example, bamboo will address the ecological and economic implications of unsustainable fibers. Bamboo is a biodegradable renewable resource, requires less water and can sequester carbon. It has a natural anti-fungal and anti-bacterial agent called "chinone" or "Kun". It therefore does not need pesticide. Kun also

inhibits bacteria from growing and spreading in textile [59–61]. Table 3 shows the ecological impact and sustainable adaptation measures of different T&C materials, collated from [13,56].

Table 3. Ecological impact and sustainable adaptation for different T&C materials.

Material	Advantages	Ecological Impact	Sustainable Adaptation
Cotton	It is biodegradable. Not discoloured by ultraviolet rays. Soft and breathable. Flame-retardant, hypo-allergenic and easy to wash.	Huge amount of land for cultivation. Great amount of water for processing. The cultivation requires great amount of fertilizers and pesticides.	Increased use of natural fibers like hemp, flax, linen and nettle that requires less water, fertilizers and pesticides.
Polyester	Requires lower water use compared to cotton. Can be wash at low temperature. Dries fast and rarely requires ironing. Can be reprocessed into virgin (new) fibers.	Made from petroleum, and do not biodegrade. Laundry of polyester releases microfiber plastics and enters human trophic level (food chain).	Development of bio-based polyester (biosynthetics) from renewable sources – starches and lipids from corn, sugar cane, bamboo, beet or plant oils.
Man-Made Cellulose (from wood pulp) – Rayon	Produced from renewable plants. Biodegradable.	Unsustainable sourcing of cellulose. Chemicals used in processing are not recovered.	Development of innovative and sustainable materials that grow fast, requires no irrigation or pesticides e.g. Lyocell, Bemberg, Cotton liner and Pinatex.

"Sustainable fibers"—the thinking, practice and use of material fibers that reduces pollution—are critical to a circular T&C industry. Materials, for example, like Lyocell, made from cellulose, are produced in a closed-loop manufacturing cycle. Therefore, 99% of the chemicals used to make the material fibers are recycled. Utilization of sustainable fibers is central to reducing environmental implications of textile production [9]. Eco-design is very important to scale challenges posed by reprocessing of waste textile at their end-of-life. The lyocell process can also be utilized to produce textile from bamboo, and the fabric is known with the brand name Monocel.

Bamboo textiles require simple technology to produce and are thus inexpensive. Bamboo fiber can be processed mechanically or chemically. In mechanical processing, the woody component of the plant is crushed. Enzymes are then used to disintegrate the bamboo walls so that the fibers can be

mechanically scoured out and spin to yarn. Products of bamboo fiber produced by mechanical process are called bamboo linen [62]. The chemical process is further categorized into two: (i) hydrolysis alkalization with the multi-phase bleaching principle; and (ii) the viscose process used to produce rayon and the closed solvent spinning loop, which is the same with that used in production of Lyocell fibers (NMMO dissolution of cellulose). Many studies have questioned the "sustainability claim" of bamboo produced fiber or fabrics. Chemicals used in dissolving bamboo cellulose (that is the viscose process for production of rayon - bamboo rayon) materials are highly toxic, and about half of it may not be recaptured. Similarly, bamboo linen is labour intensive [60–62]. However, the Lyocell process significantly reduces the ecological impacts associated with viscose process of bamboo fiber and therefore is relatively environmental-friendly, as 99.5% of the chemicals utilized during the production process are recovered and recyclable. Accordingly, US Federal Trade Commission (FTC) distinguishes between bamboo rayon and natural bamboo fabric, in clothing labeling and claims, to protect consumers from deceit. It is therefore inaccurate and naïve to oversimplify that all bamboo products are processed in a similar way [60]. Companies such as Litrax AG Limited and Tencel are now using bamboo fibers in textile production.

Despite the great potential of bamboo, it is under-utilized. The National Forest Policy pays little or no interest to the expansion of bamboo forest. Bamboo production is left mostly to informal and rural farmers. However, its potentials are widely tapped in countries like China and India. In Nigeria's National Forest Policy approved, bamboo is characterized as one of the various non-timber forest plants. This categorization signifies that bamboo does not merit massive government support. Recent global policy on forestry focuses on the relationship between deforestation and climate change, loss of biodiversity and livelihoods. Conversely, the main concern for lower-middle income countries like Nigeria is the supply of timber to meet growing demand. The possibility of developing bamboo as a critical resource with export capacity is inhibited by its continuous categorization as non-timber forestry. It is imperative that the beneficial uses of bamboo are articulated to encourage further development of bamboo forestry [61,63].

3.1.4. Renewable energy

Sustainable energy is an integral component of sustainable production [35]. Even the production of renewable natural fibers such as cotton currently uses non-renewable energy supply. Recycling of textile waste also requires energy for the different processes [41]. Apart from recycling and circularity of material, another major goal of sustainability and circular economy is reduction in greenhouse gas emission. Textile production is energy-intensive. Textile industry accounts for 10% of CO_2 emissions [2], and it releases 1.2 billion tonnes of CO_2 [14]. Circular management (recycling) of EOL products has been shown to require less energy and virgin raw materials (and invariably GHG emissions) than production processes of new products. For example, incorporating 12% recycled content in denim textile consumes 4.2% less energy and reduces CO_2 emission 3.8% compared to production new denim. Similarly, yarns produced with 80% recycled uniforms resulted to reduction of energy use by 42% and CO_2 emission by 33% compared to non-recycled yarn [5].

Development in using T&C for energy recovery is growing. For example, cotton which has high cellulose content (85–95% dry wt.) has unique possibility to be used for biofuels. The use of NMMO in treatment of cotton/polyester blend has been shown to produce methane. The process can also be applied to other cellulose materials such as viscose [45–47].

3.1.5. Effective waste management system

Poor management system of the country poses a challenge to efficient recovery of textile wastes for recycling. Without the "culture" of waste separation at source, efficient collection and sorting system, "waste" cannot become a valuable resource. Therefore, there is a need for re-orientation to view waste as a potential raw material, whose sustainable recycling offers social, economic and environmental benefits. The issues that have critically limited Nigeria's waste management include financing, lack of government support, lack of efficient legislation, poor environmental sensitization and lack of technical capability.

High proportion of Nigerians live under poverty (earns less than $2/day). Accordingly, to foster circular principles in managing end-of-life clothing, financial incentives and proper waste management principles (reduce, reuse, segregation at source, recycle) will have to improve. In CE, consumers are not only buyers but they are also suppliers (by reverse logistics). Hence, there is need for change in consumer behavior [14,31]. There exists a supply and demand gap. This is because of poor relationship between waste producers and potential users. Hence, the need for improved means to collect, manage and transfer information [3].

Currently, there are some encouraging programs to support circular economy. For example, in Lagos State, the Lagos Waste Management Agency has developed a program dubbed Blue Box Recycling Initiative (BBRI). The blue boxes are distributed to households to collect recyclable materials like cans, glass, paper, and plastics. The aim is to recover around 50% of recyclable materials. The materials are collected once a week. The non-recyclable wastes are collected in black bags. Two major companies promoting recycling in Lagos are We Cyclers and Recycle Points. Recycle Points uses an incentive model to collect recyclable materials from registered post-consumers, households and corporate organizations. The clients are compensated with "points" which can be exchanged for cash and/or households' items when accumulated. At present, there are about 8,000 registered patrons. 400,000 recycle points earns a customer ₦100,000 ($260, at $1 = ₦412). The company collects the materials door-to-door [30]. This model is feasible for our proposed system for textile (and other EOL products) recovery, reuse and reprocessing.

Consequently, it is important that free market system work together with waste management agency to collect, sort, and grade and deploy to either re-sale, reuse, or reprocessed (open-loop or close-loop cycling). For that to work properly, there must be policies encouraging and incentivizing enterprises to use recycled materials. Applications such as upholstery, disposable diapers, napkins and tampons, filling material, cleaning rags, etc. offers unique advantage to recycling used textiles. The market for disposable diapers and napkins are huge in Nigeria. The incentives to companies using recycled materials should include special tax discount, grants and seed capital to startups. Accordingly, waste management should be improved in the country. The first step towards that is funding and establishing best practices in the sector.

3.2. Generalization of the paper

The greatest population increase across the globe is occurring in Africa and Asia, which also happens to be the major destinations of second-hand clothing (SHC) and other T&C. Nigeria shares a commonality with many of the countries in the area that have immense potential and natural resources and has the potential to be a major producer of textile and clothing. Nigeria also shares commonality

with many developing countries where circular economy and its principles are not yet established. One of the major environmental problems of developing countries is poor waste management system. The poor infra structure, lack of legislative frameworks, and unhealthy business environment have limited adoption of CE in managing end-of-life products (including textiles and clothing). The urge for industrialization, accelerated economic growth, and the need to improve the quality of life necessitate that many developing countries generally neglects the concept of sustainability. The assumption that sustainable practices conflicting with economic growth is common [64]. Therefore, this paper can be generalized to other countries that confront the same challenges. Implementation of CE in the areas will support frugal innovation. Frugal innovation (FI) is a *"design innovation process in which the needs and contexts of citizens in the developing world are put first in order to develop appropriate, adaptable, affordable, and accessible services and products for emerging markets"* [65]. Accordingly, transition to CE will provide value at lower costs [31]. Coupled with the relatively cheaper labour, it can be a major drive for export-driven and local economy.

Transition to CE will also offer to developing countries the opportunity to integrate sustainability in their economic development programs. This is critical considering that increasing population and economic growth suggests that developing countries such as Nigeria, (including China and India) will be a major contributor to environmental pollution (GHG emissions, waste production, etc) and resource depletion in the nearest future. Therefore, deploying CE will not only provide for inter and intra generational equity in resource use, it will promote quality and healthy environment [66,67]. It will foster proper and adequate waste management system and improve the well-being of the people.

4. Conclusions

Textile and clothing industry value-chain are associated with environment pollution (solid wastes, effluents, pollution, greenhouse gas emissions, etc), and unsustainable resources use (raw materials, water, energy, etc). T&C industry is the second largest greenhouse gas emitter. Large amounts of water, resources and chemicals are used in production. These factors describe the basic challenges, which the paper addressed. Like other waste streams, textile and clothing wastes are not properly managed to support sustainable practices. Wastes are generally disposed to dumpsites. Adequate policies, laws and institutional capacity which drives proper waste management system are needed. Factors unique to Nigeria—waste management system, production and consumption pattern, technology and existing infrastructure—suggests that there should be local options to sustainable management of T&C wastes. For example, Nigeria is a major receptor of second-hand clothing (SHC) from developed countries. Our paper advocates for free market system, together with efficient waste management system, to enable scaled-up recovery and recycling of post-consumer wastes. However, for production wastes, there should be an increased drive supporting enlarged use of sustainable fibers, renewable energy, collection, reuse and integration of their wastes in further production of new fibers or cascading to other relevant production processes. Three ways which support increased reuse and recycling of T&C and sustainability of the industry are: new business model (slow fashion, re-sale, rentals, and subscription), regenerative production processes and materials, and effective waste management system and their components. Circular management of end-of-life T&C will support improved sustainability in waste management in Nigeria.

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Conflict of interest

The authors declare no conflict of interest.

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