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Non-Metallic Material Science

Volume 4 • Issue 2 • October 2022 ISSN 2661-3301(Online)

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Volume 4 Issue 2 · Special Issue · October 2022 · ISSN 2661-3301 (Online)

Non-Metallic Material Science

Editor-in-Chief

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EDITORIAL

Eco-friendly Sustainable Multiphase Polymer Systems for Advanced Functions

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ARTICLE INFO

Article history
Received: 27 December 2021
Accepted: 31 December 2021
Published Online: 15 January 2022

When Eric Fawcett and Reginald Gibson discovered polyethylene accidentally, they never realized how useful their discovery will be for mankind, similar to how Charles Goodyear's idea of adding sulphur to polyisoprene would revolutionize the tire and other rubber industries. Although those discoveries centuries ago have never realized their current impact, however, the fact is undeniable on how polymer science has conquered the world, gaining an irreplaceable position from a utilitarian perspective. We are currently bombarded with multifarious polymer compositions which differ on the basis of source, origin, and dimensions. They can be broadly classified on the basis of source as fossil-based and bio-based; depending upon origin as natural and synthetic; and as bulk, micro-and nano-sized based on the dimension of the system. Depending on the constitution and form of the end products, polymers are further categorized as blends, composites, nanocomposites, gels, and interpenetrated polymer networks (IPN) [1].

Polymers have infiltrated almost every industry and are an integral part of our day-to-day lives. Presently, humans are in a place where life without polymers seems impossible. Not only the industries, but the medical sector, packaging sector, personal care, cosmetics, automotive

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DOI: https://doi.org/10.30564/nmms.v4i2.4278

and electronic sectors are hugely dependent on the various polymeric products. In the 20th century, the use of plastics had innumerable advantages being cost-effective, easy handling, and wide availability. The blessings of the 20th century however turned into an impending curse on our generation. Depletion of fossil fuels, as well as the excessive use of plastics, damage happening is a red flag for the environment. The widespread use of plastics- a broad term used for non-biodegradable polymers in the food packaging industry has led to serious health issues. Due to the leaching of chemicals into food, disposal issues ultimately lead to either incineration of plastics causing pollution or dumping in landfills or water bodies further damaging the soil and water. Plastics degrade into microplastics which get into the lower strata of the food chain from the aquatic lifeform and finally reach the top of the food chain. Although plastic recycling is an excellent step to encounter, is recycling a solution? Is it even taken seriously? How much recyclable products are undergoing recycling and reuse is a question to ponder?

The alternative is not to put a period on plastics, but to find eco-friendly and sustainable solutions to get rid of the infliction we have created over the years. There are plenty of options to choose from. Over the years several international organizations have taken the initiative to counter plastics. The world health organization in 2019 has called for more research on microplastics and a crackdown on plastic pollution. UNWTO and UNEP have taken an initiative towards Sustainable Development Goals with The Global Tourism Plastics Initiative to unite the tourism sector behind a common vision to address the root causes of plastic pollution. It enables businesses, governments, and other tourism stakeholders on an international platform to lead by example in the shift towards a circular economy of plastics.

With the onset of COVID-19, the already out-of-control plastic problem has intensified with reports stating the generation of more than 8 million tons of pandemic-associated plastic waste globally. Slashing plastics and switching to other sustainable options are needed to preserve our environment and have the resources available for posterity.

Plenty of constructive work is being done towards attaining SDG. A huge mind-shift in research has happened to attain SDG with polymer research accelerating towards environmentally compatible systems. The polymer inherently has different properties. It can stand alone but predominantly multi-component systems are required to achieve an objective. Multiphase systems have been used for generations now. Biodegradable polymeric systems like nanocellulose, lignin, chitosan, carrageenan, PLA, PHA, PBS/A, PCL, PBA/T derivatives have profound applications in industry [2,3] Modification can be brought during copolymerization to tailor according to the need.

The use of different forms of polymer exerts discrete properties serving the requisite functions. In this direction lately, a lot of research is being diverted on lignin. It has been derived from agricultural waste similar to cellulose and is being utilized to produce eco-friendly composites and blends in packaging, biomedical, and energy storage applications [4]. Similarly IPN for hydrogels of PVA and chitosan, gelatin and alginate have shown potential in biomedical applications due to their enhanced elastic and mechanical properties [5,6]**.** Nanocellulose, a potential filler in several composites, blends, and especially in emulsions and other water bases polymer systems, is highly stabilized as a resultant of its unique structural and surface chemistry owing to the presence of numerous hydroxyl groups on its surface which can be functionalized and tweaked as per the requirement[7]. Hence it is considered to be an ideal option for the replacement of toxic additives and property modifiers in nanocomposite materials [7]. Expediting the research in sustainable eco-friendly systems can enable the industry towards safer and greener scientific productions with enhanced functionality, a step ahead to a greener economy.

The phase morphology hence in various multicomponent polymer-based systems governs the physical characteristics allowing control over material designs and development of new polymeric systems. The recent advances concerning morphological, rheological, interfacial, physical, fire-retardant, thermophysical, and biomedical properties of multiphase polymer systems have a beating over the non-eco-friendly counterparts. Advanced applications with enhanced physical, mechanical, thermal, electrical, magnetic, and optical properties are undertaken with a step closer towards the green economy.

Ideas should be brought forth to create eco-friendly sustainable polymers systems which can change the concept of classifying every polymer as "the plastic" and eradicate this negative terminology associated with polymers in the mind of commoners.

The objective of this special issue is to create a common ground for the discussion of eco-friendly sustainable technologies incorporating multiphase polymer systems. The present issue is to survey the recent developments in such green systems covering the actual scientific synthesis procedure, incorporating characterization and identification of different physical, chemical, interfacial and thermophysical properties as well as encompassing the headway achieved in this area. All the recent scientific advancements in the field of green, sustainable multiphase polymer systems are anticipated to share their work to put forth a special issue which can strengthen the core of the scientific community to work towards Environment Sustainable Technologies.

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REVIEW

Biopolymers Applied to Packaging: A Brief Literature Review on Their Impact on Sustainability

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ARTICLE INFO

Article history
Received: 24 December 2021
Accepted: 23 March 2022
Published Online: 14 April 2022

Keywords:
Packaging
Biopolymers
Sustainability
Circular economy

ABSTRACT

The replacement of fossil raw materials by renewable alternatives is imperative. Renewable, biodegradable, and compostable polymers are options to be developed and adopted. Embedded in this concept, the present study evaluates whether biopolymers are sustainable alternatives to replace traditional polymers used in packaging, such as polyethylene. To that end, a systematic literature review (SLR) was carried out on biopolymers applied to packaging, with an analysis of its impacts. Three sustainability criteria were adopted: a) Criteria for Developing Sustainable Packaging; b) Goals of Sustainable Development; and c) Circular Economy Criteria. The Methodology Section presents the state of the art of potential polymers for packaging and their characteristics related to the evaluation criteria adopted based on the SLR. Through data collection, it was observed that advanced obtaining techniques enable polymers economically and that, environmentally speaking, there is a positive consensus about some types of those materials. However, technological maturity and productive scale capacity are necessary to reduce costs in a competitive scenario with conventional polymers.

1. Introduction

According to the Brazilian Bioinnovation Association, bioeconomy must consider the advanced scientific knowledge in order to promote innovations in industrial processes that use renewed resources. It also calls for the impacts of those advances to be directed towards the circular economy for the benefit of society in general and the environment [1]. Other definitions of bioeconomy are found in researches, policies, strategies among other sources [2,3]. But all of them share a common sense: the recognition that natural resources are limited and must be used effi-

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DOI: https://doi.org/10.30564/nmms.v4i2.4268

ciently. This statement correlates to economic growth, development, and environmental protection [4]. Regarding society's concern about bioeconomy, plastic materials are in the spotlight, whether in what concerns the use of non-renewable materials or in the generation/disposal of waste. Between 1950 and 2019, 9210Mt of plastic was produced. Up to 2015, 6300Mt of waste was generated and only 21% was recycled or incinerated. The other 79% was accumulated in landfills or improperly disposed of in the environment. About 38% of this material composed basically of materials from non-renewable sources was used by the packaging industry [5]. Embedded in the circular economy context, biopolymers can be designed to be degradable or compostable within months or years. They can also contribute to carbon capture due to its mostly plant-based origin and mitigate both the negative impacts arising from the consumption of fossil-sourced material [2]. Figure 1 illustrates the carbon cycle of fossil-sourced polymers and that of biopolymers.

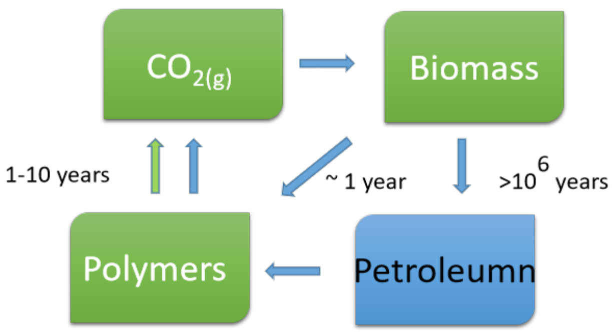

Figure 1. Carbon cycles of conventional polymers and biopolymers [6]

Biopolymers stand out in biomedical [7], 3D printing filaments [8], agricultural [9], electronic [10], and coating [11] applications. Advances in obtaining technologies and increased productive capacity make it economically feasible to use this material in packaging [12,13]. In order to be competitive, they must meet the expected requirements in packaging such as mechanical strength, thermal resistance, ease of processing, water-vapor barrier properties, and durability [10]. Although the environmental impact of packaging is widely reported and criticized as environmental pollutants, packaging plays an important role in reducing waste. It is estimated that the environmental damage for not using packaging would be much greater, considering that 70% is used for food packaging [14].

1.1 Motivations and Goals

The diversity of renewable materials for packaging, obtaining and processing techniques introduced in recent years has contributed to the emergence of new paradigms. Such scenario has uncovered a lack of literature that cross-references to explain common issues within the packaging supply chain, with the adoption of criteria to guide the development of those new materials [15]. The purpose of the present review is not to introduce a new paradigm, but to investigate issues regarding the use of polymers as packaging materials and their impacts on sustainability. Therefore, the present review aims to answer the following research question:

RQ1: Are polymers sustainable alternatives to replace conventional polymers in packaging applications?

In order to address this issue, a systematic literature review (SLR) was carried out to identify the state of the art of biopolymers applied to packaging and their impacts on sustainability criteria.

1.2 Packaging

Packaging may be defined as a product made of material of any nature used to contain, protect, transport, distribute, and present commodities, from natural to processed material goods, from producers to consumers [16]. Complex concepts can be used to evaluate whether the packaging is sustainable. But mainly it must address the use of innovative and functional materials that promote economic and environmental health [17]. In this regard, packaging must meet some principles for sustainable materials such as: *functionality,* effectively protecting the packaged product; *efficiency*, consuming a minimum of materials, water, and energy; *cyclic*, generating minimal waste; *safety*, clean and safe and causing no risks to the environment [18,19]. For the development of packaging, a set of mechanical and chemical properties is evaluated. Throughout the present review, it was observed that permeability and mechanical strength of biopolymers are among the greatest concerns and have been the sources of several studies [20,9,12,21].

1.3 Biopolymers and Packaging

Biopolymers are polymers derived from renewable sources that can be biodegradable or non-biodegradable. Non-biodegradable products play a role in capturing CO_2 emissions and may be used in infrastructure applications such as pipes, building materials, and roofing. In turn, biodegradable products play a role in short to middle life cycle products, neutral CO_2 balance, and projected degradation time designed according to application [2]. Currently, packaging is in the spotlight of scientific research that seeks the development of sustainable materials [22,23]. And biopolymers are at the forefront as substitutes for fossil-sourced materials. However, the mechanical and water vapor barrier properties are relatively poor when compared to conventional polymers [17]. When technical-commercial requirements are put together, it is possible to explain why there are few commercially successful biopolymers [24]. On the other hand, since 2009, the productive capacity has been increasing and confirming production forecasts. Although there are small divergences between the production forecast and what was actually produced, the projections shown in Figure 2 for the coming years are for an increase in production capacity [25].

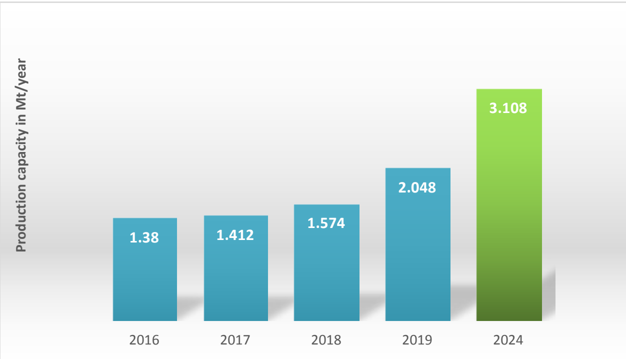

Figure 2. Global biopolymer production capacity [26]

In addition to their rising production capacity, polymers have a technical potential to replace 90% of conventional materials [27]. In order to overcome some technical deficiencies, the use of reinforcements can promote properties such as antimicrobial characteristics for food product protection [12].

1.4 Types of Biopolymers

The diversity of raw materials for obtaining sustainable polymers is subdivided into carbon dioxide, terpenes, vegetable oils, and polysaccharides. The present research focuses on groups of materials with characteristics applicable to packaging, among which polysaccharides showed the greatest potential [24]. Polysaccharides are polymers found naturally in the environment. With minor modifications, they are polymerized to obtain the desired material, such as starch, cellulose, lignin and hemicellulose [10]. The production of biopolymers from polysaccharides is one of the most studied alternatives. Those carbohydrates are abundant in nature and can be easily extracted and processed [24]. This processing involves breaking them down into monosaccharides from starch- or sugar-rich sources to obtain glucose. With this basic structure, carboxylic acids can be obtained [17]. Subsequently, these acids are polymerized through chemical reactions or enzymatic routes to produce the desired monomers. Vegetables such as sugarcane and corn are examples of sources of polysaccharide that can be transformed into biopolymers, such as polylactic acid (PLA) and polyhydroxyalcanoate (PHA) [28,29]. Another possible route is through biomass fermentation to produce methane and subsequent conversion to ethanol, to obtain Bio Polyethylene Terephthalate and polymerization of Bio PET (Polyethylene Terephthalate) and Bio PE (Polyethylene) [2].

1.4.1 Polylactic Acid (PLA)

Lactic acid is produced through the microbial fermentation of starch or sugar from corn, potatoes and sugarcane, with lower manufacturing costs and higher yields, but can be obtained by chemical synthesis. Subsequently, it is transformed into polylactic acid by polycondensation [8]. This biopolymer has properties that can replace petrochemical polymers in packaging applications, including those in which there is contact with food, approved by the US Food and Drug Administration (FDA). Therefore, it can be used in films, trays, and packaging for that purpose [24,30,8]. In terms of its life cycle, PLA can be recycled, degraded, and metabolized naturally in soil in an aqueous environment. However, its degradation capacity is reduced [2]. Chemical recycling through catalysis is preferred and, in addition to the original monomer, can provide other products depending on the technique used. Composting under anaerobic conditions can show 90% degradation in a 60-day period [10]. With regard to greenhouse gas (GHG) emissions, there can be a 40% reduction and a 25% reduction in non-renewable energy use when compared to petrochemical derivatives [31,32].

1.4.2 Polyhydroxyalkanoates (PHAs)

Polyhydroxyalkanoate is a type of biopolymeric polyester similar to PLA, but with distinct physical properties due to its low glass transition temperature (-35 °C to 10 °C) [33] when compared to PLA [34]. They are obtained by sugar fermentation, collected directly from microorganisms without the need for isolating monomers that are synthesized by controlling the growth conditions of bacteria. This second-generation biopolymer has been intensively studied, with more than 150 types of monomers from this class of biopolymer being reported [35]. Its biosynthesis takes place in an environment with low concentrations of nitrogen, phosphorus, oxygen, and excess carbon [36]. Figure 3 shows the chemical structure of PHAs.

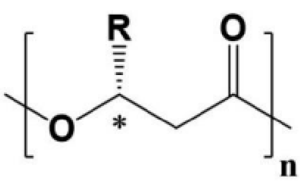

Figure 3. Chemical structure of PHAs [36]

PHAs are semicrystalline biopolymers with thermal properties that vary with the nature of the radical group present in the monomeric structure. Families of PHAs have distinct mechanical, thermal, biocompatibility, and biodegradability properties [37]. Polyhydroxybutanoate (PHB) is one of the most studied PHAs. It is used for food packaging and in medical applications such as tissue engineering [38] and in studies related to the development of PHB-based vaccines [39]. In degradation studies, it degraded by 90% through composting in 14 days in aqueous media, soil, and in industrial composting systems [2,10]. Despite being biopolymers still with low industrial scale production (up to 10,000 t/a), currently two companies stand out in the global market: Kaneca and Danimer [40].

1.4.3 Polybutylene Succinate (PBS)

This biopolymer, already available on an industrial scale, comes from glucose fermentation producing succinic acid with subsequent polycondensation of the bioderived 1.4-butanediol to obtain PBS, which can be degraded by microorganisms [41]. In general, this polymer is expensive and has few applications, as it has low mechanical properties. PBS films can have an elasticity modulus of up to 380 MPa and 15% elongation at break [42]. In order to circumvent those issues, some studies related to the application of those polymers to packaging consider mixing them with other stronger and cheaper polymers, such as PET and humic acid [42,43]. For packaging, it is used to promote a water vapor barrier and has recyclability [24]. Regarding degradation, in just 96 days, 3% of the material degraded in anaerobic medium and in aerobic media with enzymes. Significant degradation was observed in just 4 days [44,45]. Figure 4 shows the chemical structure of PBS. It is an aliphatic polyester.

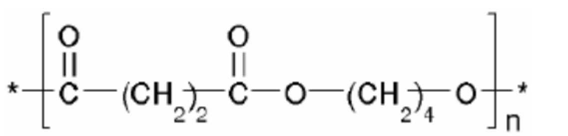

Figure 4. Chemical structure of PBS [33]

1.4.4 Polyethylene Furonoate (PEF)

PEF, whose structure is shown in Figure 5, is a promising substitute for conventional polyethylene terephthalate (PET). Although it is not commercially available, its pilot-scale production is expected to grow in the coming years. This material is copolymerized by polycondensation of furanedicarboxylic acid (FDCA) and ethylene glycol, compounds that can be obtained from renewable sources of glucose and fructose. The resulting polymer is analogous to PET, with superior water vapor barrier characteristics and oxygen permeability. Due to its similarity to PET, the possible applications are the same [46,35]. It is important to emphasize that the structures for polymerization, oxidation, and recycling are also equivalent to those of PET, which may accelerate its development. But, due to the current low production scale, its cost is still high. A disadvantage of PET is its lack of degradation capacity due to the presence of aromatic esters. However, other points favor its sustainable development, such as the 55% reduction in GHG emissions when compared to the conventional analogue [47,48].

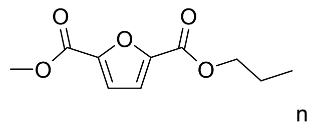

Figure 5. Chemical structure of PEF

1.4.5 Cellulosic Materials

Cellulose is known as one of the first polymers to be commercially used in packaging. Cellophane and cellulose acetate, whose structure is shown in Figure 6, have been available since the early 20th century. However, these materials have limited use in packaging [24]. Cellophane is a thin, transparent film, obtained from cellulose and produced through the viscose process. Unfortunately, that process relies on hazardous material. As it is highly hydrophilic, it loses mechanical strength and water vapor barrier in the presence of moisture. They are easily degraded in aqueous media, in soil, and in industrial composting systems [35,2].

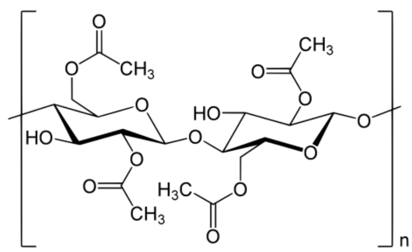

Figure 6. Chemical structure of cellulose acetate.

1.4.6 Bio PET

The production of this material involves starch degradation, glucose fermentation, ethanol dehydration, ethylene oxidation, and hydrolysis of the final product. Despite its complexity, this material can provide a 20%-25% reduction in GHG emissions when compared to the fossil-sourced PET equivalent [49,10]. They do not degrade in any type of medium, but are recyclable [2,35].

1.4.7 Bio PE

Bio PE is obtained from the dehydration of ethanol sourced exclusively from sugarcane. The polymerization of ethylene provides a polymer identical to the fossil-sourced equivalent [50]. This method is controversial, as it participates in a linear life cycle and potentially ends up in the regular trash or in the environment [10]. On the other hand, sugar bagasse waste can be used for energy generation at the processing plant. Due to its chemical equivalence and petrochemical type, the same applications have been identified for packaging, cables, fabrics, and automotive components [27]. Bio PE does not degrade in any type of medium, but is recyclable [2].

1.5 Sustainable Development

Sustainable development is defined as "development that meets the needs and aspirations of the present generation without compromising the ability of future generations to meet their own needs" [51]. Metrics for product and process development, such as the Life Cycle Assessment (LCA) approach, can be used to quantify sustainability performances. This technique is based on the quantification of energy and flow of the materials used in each stage of the production cycle [52,53]. Another technique that can be used is the *Green Design Metrics (GDM)*, which provides a more comprehensive assessment based on the principles of sustainable chemistry, summarized by the following topics: the use of renewable and local sources; atom economy; the use of less hazardous reagents and syntheses; lower waste generation; maximum energy efficiency; products designed for recycling and degradation; and cost efficiency [10]. Quantitative metrics for assessing environmental sustainability are not universally accepted as metrics for assessing economic sustainability, and more comprehensive models have been evolving. However, those approaches have been criticized for not sufficiently valuing social issues, demanding the need to include this topic in a social agenda to identify possible conflicts of interest [54]. For a qualitative assessment of the biopolymers presented in the current research, three sustainability criteria were evaluated during the literature review: 1) Sustainable packaging development [15], 2) Sustainable Development Goals [55], and 3) Circular Economy Criteria, consisting of the directives of the European Waste Commission 2008/98/CE [15] and the US Environmental Protection Agency [56].

Criterion 1 - Development of sustainable packaging

Sustainable Packaging Coalition (SPC) is an organization that seeks to give its members a voice in developing packaging that is good for the consumer and the environment, bringing together stakeholders to discuss issues related to packaging sustainability. Due to the focus on packaging in the present research, the criteria of this organization will be used for the analysis of biopolymer materials listed in this review. SPC uses the following approaches for the development of sustainable packaging:

A - It is beneficial, safe and healthy for individuals and communities throughout its life cycle;

B - It meets market criteria for performance and cost;

C - It is sourced, manufactured, transported, and recycled using renewable energy;

D - It optimizes the use of materials from renewable or recycled sources;

E - It is manufactured using clean production technologies and the best practices;

F - It is manufactured with healthy materials throughout its life cycle;

G - It is physically designed to optimize materials and energy;

H - It is effectively designed and used in close-loop biological and/or industrial cycles.

Criterion 2 - Sustainable Development Goals (SDG)

According to the 2015 report of the United Nations Organization, growing global awareness of sustainability is changing consumer preferences. In order to meet the 17 main goals detailed in another 168 objectives and 243 indicators, biopolymers enable a new economy vis-à-vis conventional polymers. The 2030 Agenda [55] was declared to meet the wishes of present-day society until 2030. The main objectives and indicators were analyzed together with the literature review, checking whether the biopolymer life cycle is positive, negative or does not interfere with the analyzed SDG.

Criterion 3 - Circular Economy

The *European Commission* [57] establishes a waste hierarchy with five basic levels in Directive 2008/98/EC: 1) prevention, 2) reuse, 3) recycling, 4) other recoveries, and 5) disposal. Similarly, the US Environmental Protection Agency (EPA) has a four-level waste management hierarchy: 1) source reduction or waste prevention (including reuse), 2) recycling (including composting), 3) combustion with energy recovery, and 4) landfill disposal [56]. The concepts of those two directives were unified to analyze the concept of circular economy globally with respect to the biopolymers presented. Therefore, in order of preference, the solid waste management criteria are:

a) reduction, ability to use less mass of material;

b) reuse, reutilization of collected material without changing its form;

c) mechanical recycling, using only mechanical processes;

d) chemical recycling, converting the material into monomer or basic chemical structure;

e) biological recycling (composting), degradation into CO_2 (or CH_4) and H_2O;

f) energy recovery, incineration of material for energy generation;

g) sanitary landfill, disposal in a regular landfill.

2. Discussion

The availability and costs of materials from renewable sources impact the feasibility in using those materials in packaging [17,58]. Other factors that hinder the analysis of sustainability in biopolymers are related to the diversity of resources used to obtain them when compared to fossil-sourced materials [59]. The competition with areas destined for food production is discussed in some forums, but it is controversial. According to IfBB's forecast for a production scenario of 3.108 Mt, in 2024 the allocation of land available for cultivation to meet this demand will be less than 0.2% [26]. Based on [60,61] reported that, for a production scenario of 300 Mt/year of PLA, only 0.9% of the 5 billion hectares of agricultural land available for the production of corn will be needed. Even so, the transition to obtain biopolymers from non-food sources is desired, such as the lignocellulosic biomass. Besides avoiding competition with the food chain, a reduction in biopolymers costs is expected, contributing to the achievement of the SDGs established by the UN [62,2]. Although Bio PET and Bio PE are contested for having the same monomer as the fossil source, the advantages are due to the life cycle being well established by the polyolefinic pairs in addition to the renewable provenance. Another consideration about the degradation difficulty of Bio PET and Bio PEF is due to the presence of aromatic esters. A recent study found a bacterium that can accelerate the degradation of those materials, enabling them for a sustainability scenario [63]. In general, chemical recycling of biopolymers is desirable because they provide the original functional group or another one, depending on the catalytic technique used, which makes reuse in their original form feasible. Although they contribute less to the environment, composting and energy recovery are alternative end-of-life routes for biopolymeric waste [10,35]. For the material reduction criterion, advances in production technologies must be achieved to enable them at a feasible cost. For the reuse and mechanical recycling criteria, waste management must be improved to the point where the type of biopolymer can be identified. Disposal in sanitary landfills, despite being the least desirable destination, does not cause extra risks, in addition to those already existing in this type of environment [8]. Among the advances found, catalysis is a technique that efficiently speeds up the obtaining process, with a cost lower than that of currently used processes. This technique can also be used in degradation by chemical or biological recycling. Many obtaining methods are available, but they are in the process of evolution with advantages and disadvantages to be considered in biopolymer design [10,35]. Figure 7 relates the renewability of raw material to the degradation capacity of the polymer. Materials in the upper-right quadrant in Figure 7 are desirable for packaging applications within the circular and sustainable economy.

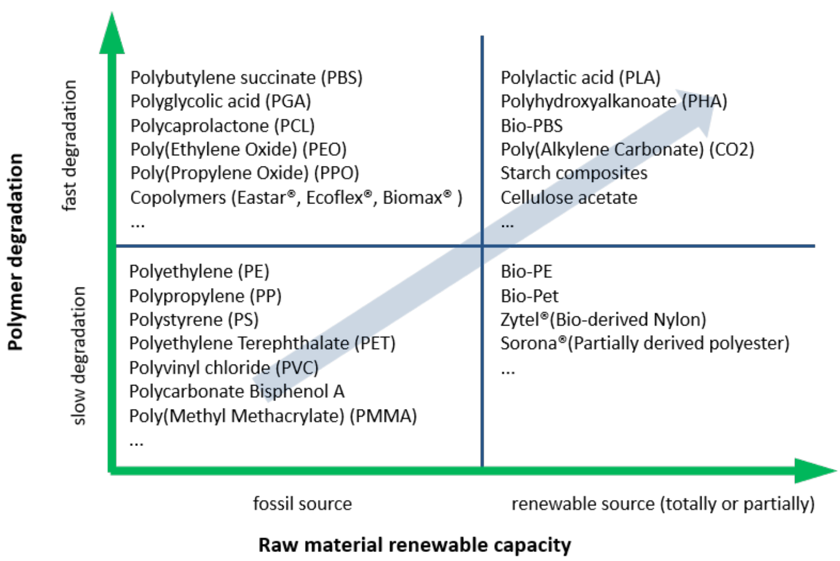

Figure 7. Classification of polymers based on raw material renewable capacity and polymer degradation [10]

In order to mitigate the negative effects of improper disposal, a biodegradable plastic is desired. The type of engineering required for this function is the transformation of the material - by microorganisms - essentially into CO_2 and H_2O, which is then converted into biomass through photosynthesis, completing the life cycle [10]. Some biopolymers such as PBS, PHB, and PLA can act as environmental remediators, that this, with the ability to remove contaminants from the soil through sorption and denitrification mechanisms. Biopolymers in contaminated systems act by absorbing contaminates or providing carbon and energy to microorganisms to facilitate denitrification [8].

2.1 Analysis of Criteria for Developing Sustainable Packaging

Among the economic factors, the low added value of packaging is one of the main barriers to the use of biopolymers for this application. Table 1 evidenced this difficulty, in the light of criterion "B") it meets market criteria for performance and cost, where the authors reported the high cost of those materials associated with technical performance issues.

Favorably, through more efficient processes, new methods of synthesis and reinforcement additions are enablers for use in packaging. Another barrier to make them even more sustainable is obtaining them from non-food sources, avoiding competition with this chain [35]. PEF presented many technical limitations, mainly in obtaining, production, and end of life. But it is a promising substitute for conventional PET. Cellulosic materials demand hazardous components for production in packaging applications that require low permeability, and are then penalized in item "F") it is manufactured with healthy materials throughout its life cycle. Bio PE and Bio PET enable polymers for packaging regarding cost and performance. An important consideration is that life cycles are relatively equivalent to the corresponding polyolefins (PE and PET), suggesting less sustainable materials as they are not biodegradable. Positively, in general, biopolymers meet most SPC criteria. But their disadvantages are: performance, cost, and waste recovery properties. Composites are being studied to improve these characteristics, including potential negative effects when in contact with food, such as migration and toxicity [35]. As can be seen, the criterion related to waste recovery, item H, was not fully met. This issue will be further discussed within the Circular Economy criteria.

2.2 Analysis of the UN Criteria - Sustainable Development Goals

This analysis brought to light the economic and social benefits for meeting the UN sustainability criteria. There was a gain in the promotion of small rural properties encouraged by the increased need for raw materials to obtain biopolymers. This increased demand can provide those rural properties with jobs, stimulate the use of new technologies, promote the development of sustainable agriculture, and create regulations that support small producers. Preferred agricultural products should be those that have better efficiency for obtaining biopolymers, such as corn, sugarcane, and potatoes [8]. Table 2 depicts the analysis of those biopolymers highlighted in the present research regarding the impact on each of the 17 Sustainable Development Goals monitored by the UN. In some goals, no benefit was observed due to the SDG premises, for example, political issues, gender inequality, and conflict between societies, Therefore, SDG's 1, 4, 5, 10, 16, and 17 were market as "not applicable" (na) in all analyzed materials.

Some biopolymers stood out with several published

Table 1. Qualitative evaluation according to SPC criteria

Materials	SPC Criteria								Authors
	A	B	C	D	E	F	G	H	
PLA	x	na*	x	x	x	x	x	x	[26]; [24]; [31]; [32]; [59]; [10]; [2]; [30]; [35]; [8]
PHB	x	na	x	x	x	x	x	x	[26]; [10]; [2]; [35]; [8]
PHA	x	na	x	x	x	x	x	x	[26]; [24]; [10]; [2]; [35]
PBS	x	x	x	x	x	x	x	na**	[26]; [44]; [2]; [8]
PEF	na	na	x	x	x	x	x	na**	[24]; [2]; [35]; [63]
Bio PET	na	x	x	x	x	x	x	na	[26]; [24]; [35]; [2]
Bio PE	na	x	x	x	x	x	x	na	[26]; [27]; [10]; [24]
Cellulosic	x	x	na	x	na	na	x	x	[26]; [24]; [2]; [35]

x - meets criterion

na - not applicable

*possible with reinforcement additions

**under specific conditions

Table 2. Quantitative assessment according to UN criteria, Sustainable Development Goals

Materials	UN criteria - Sustainable Development Goals																	Authors
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	
PLA	na	x	x	na	na	x	x	x	x	na	x	x	x	na	x	na	na	[26]; [24]; [31]; [32]; [59]; [10]; [2]; [30]; [35]; [8]
PHB	na	x	x	na	na	x	x	x	x	na	x	x	x	x	x	na	na	[26]; [10]; [2]; [35]; [8]
PHA	na	x	x	na	na	x	x	x	x	na	x	x	x	x	x	na	na	[26]; [24]; [10]; [2]; [35]
PBS	na	x	x	na	na	x	x	x	x	na	x	x	x	na*	x	na	na	[26]; [44]; [2]; [8]
PEF	na	x	x	na	na	x	x	x	x	na	x	x	x	na*	x	na	na	[24]; [2]; [35]; [63]
Bio PET	na	x	x	na	na	x	na	x	x	na	x	na	x	na*	x	na	na	[26]; [24]; [35]; [2]
Bio PE	na	x	x	na	na	x	na	x	x	na	x	na	x	na	x	na	na	[26]; [27]; [10]; [24]
Cellulosic	na	x	x	na	na	x	x	x	x	na	x	na	x	x	x	na	na	[26]; [24]; [2]; [35]

x - meets criterion
na - not applicable
*possible with reinforcement additions
**under specific conditions

researches and advances in industrial scale. In order of relevance in the SDG analysis, they are: PHB, PHA, PLA, and PBS. In general, biopolymers presented a 14% impact on all 243 indicators, as shown in Figure 8, which summarizes the impact analysis on indicators by the SDG.

The three best rated objectives by their targets and indicators were: 2) End hunger, achieve food security, improve nutrition, and promote sustainable agriculture; 9) Build resilient infrastructures, promote inclusive and sustainable industrialization, and foster innovation; and 12) Ensure sustainable production and consumption patterns. Biopolymers meet the demands of the indicators of those objectives with 57% for SDG-2, 41.7% for SDG-9, and 61.5% for SDG-12.

2.3 Analysis of Circular Economy Criteria

Table 3 summarizes the impacts of biopolymers on the circular economy, with few studies showing the end of cycle of those materials. In the present review, with emphasis on criteria related to recycling - whether mechanical, chemical, or composting -, biopolymers showed limitations or early stages for PLA, PHB, PHA, PBS, and PEF. Due to the nature of those materials, the current recycling technologies do not fully qualify biopolymers for this important circular economy criterion. This little progress reveals the need to develop regulations for waste disposal, which are still in their early stages.

Bio PET and Bio PE already qualify for recycling systems due to their equivalence to current processes. They can be recycled in the same way as their polyolefin counterparts. On the other hand, composting and energy recovery are hampered for the same reason.

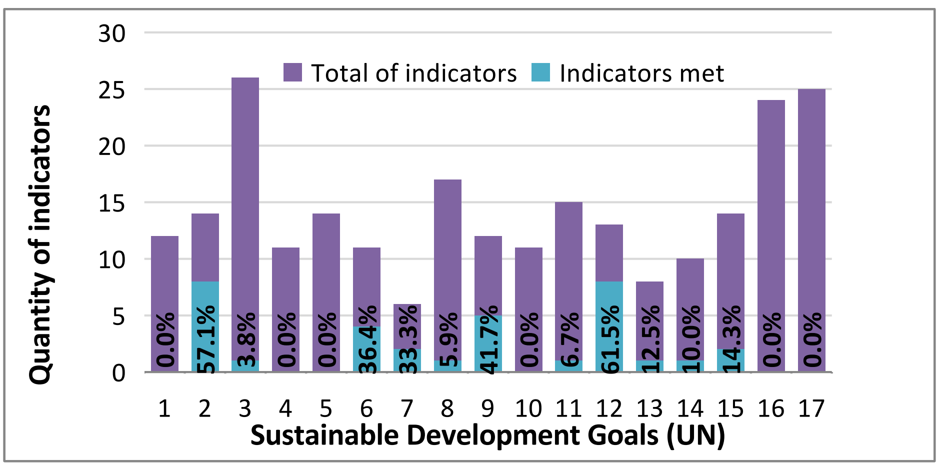

Figure 8. Number of SFG indicators x Indicators met by biopolymers (%)

Table 3. Qualitative evaluation according to Circular Economy criteria

Materials	Circular Economy Criteria							Authors
	a	b	C	d	e	f	g	
PLA	na*	x	na	x	na**	x	x	[26]; [24]; [31]; [32]; [59]; [10]; [2]; [30]; [35]; [8]
PHB	na*	x	na	x	x	x	x	[26]; [10]; [2];[35]; [8]
PHA	na*	x	na	x	x	x	x	[26]; [24]; [10]; [2]; [35]
PBS	na*	x	na	x	na**	x	x	[26]; [44]; [2]; [8]
PEF	x	x	x	x	na**	x	x	[24]; [2]; [35]; [63]
Bio PET	x	x	x	x	na**	na	x	[26]; [24]; [35];[2]
Bio PE	x	x	x	x		na	x	[26]; [27]; [10]; [24]
Cellulosic	na	na	x	x	x	x	x	[26]; [24]; [2]; [35]

x - meets criterion

na - not applicable

*possible with reinforcement additions

**under specific conditions

Source: the author (2019).

3. Conclusions

Although studies comparing biopolymers and conventional polymers are in their early stages, there is sufficient research favoring them. The main opportunities lie in evaluations of human health impacts when used in food-packaging. Specific conditions of degradation, composting, and recycling have been studied mainly using catalysts to promote these characteristics. But there is a vast field to be investigated, considering that technologies still present an initial maturity curve when compared to technologies and processes used to obtain petrochemical-based polymers. However, technical maturity and commercial reach should be attained soon. What became clear in the present study is the need to gain production scale. This way, the costs of processes in this new economy will become feasible for the use of biopolymers in packaging. Apart from the environmental aspects, economic and social gains were observed in the analysis of the SDG criteria, such as the promotion of jobs in small rural properties. In response to the research question, biopolymers depend on development and advances in specific areas to have reach as packaging materials, and scale gains should be the biggest enabler. It is important to emphasize that advances in regulations for polymer waste disposal must be urgently established if there is to be success in using this material to replace conventional polymers.

Conflict of Interest

There is no conflict of interest.

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REVIEW

Sustainable Textile Industry: An Overview

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ARTICLE INFO

Article history
Received: 9 May 2022
Accepted: 27 June 2022
Published Online: 7 July 2022

Keywords:
Sustainable
Industry
Eco-design
Manufacturer

ABSTRACT

The purpose of this study was to offer a general concept and overview of the textile industry's environmental sustainability assessment. The textile and garment industries cause environmental damage at every stage of manufacturing, from the cultivation of raw materials through the disposal of finished goods. Chemical loading, high water consumption, high energy consumption, air pollution, solid waste, and odour creation are all key environmental concerns in the textile industry. To achieve sustainable production, it is necessary to examine the performance of the textile sector while considering the three elements of sustainability. To study and locate recent and related works, five keywords were used: environmental; sustainability; eco-design; manufacturer; supply chain management. All through the life cycle of textile products, the textile sector has a substantial environmental impact. This paper illustrates how the textile industry may use strategic ways to improve ecologically sustainable textile product usage and manufacturing. A discussion is focused on how to be increased sustainability in the textile industry. This paper introduces key principles for ecologically sustainable business practices to consider (e.g., eco-design, corporate social responsibility, and green supply chain management). It is critical that all stakeholders in the textile industry, including consumers, producers, environmental protection is emphasized in the manufacture and use of textile goods by the distribution chain and customers.

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DOI: https://doi.org/10.30564/nmms.v4i2.4707

1. Introduction

Environmental sustainability, from an entrepreneurial standpoint, is a marketing plan for using processes that do not have negative effects on the throughout the life cycle of natural resources (e.g., gathering, production, consumption, durability, energy production, and disposal), the environment or natural resources are considered [1]. The environmental effects of a cotton T-shirt, for example, can be seen in these life cycle stages. Cotton cultivation involves the use of fertilizer, pesticides, and water; dyeing and spinning grown cotton necessitates the use of coal, dyes, and auxiliaries, as well as water and electricity; and T-shirt production requires the use of power generation, washing, and liquid. The collecting, processing, and application steps are repeated to obtain a reorder of T-shirts; End users purchase and wear T-shirt items during consumption; during disposal, end users discard used T-shirts, and producers dispose of excess T-shirt manufacturing or material [2]. As a result, throughout the product life cycle, energy, chemicals, and water are significant environmental effect contributors in the manufacturing industry. To ensure environmental sustainability, apparel designers should produce things using ecologically and socially responsible design approaches and trends; the supply chain must analyze the effects of their business practices on culture, economics, and ecosystem. The environmental sustainability of textile products, a vital component of today's human life, has garnered considerable attention from both suppliers and customers in recent years due to life cycle resource consumption and environmental emissions [3]. Some clothing manufacturers have emphasized sustainable development in their processes. Institutional Knights, a Canada communication and research firm, published the Global 100 Most Sustainable Corporations in the World Index, which includes manufacturers preselected based on the results of four screening methods that assessed 12 key performance indicators of ecological responsibility (e.g., resources and energy usage efficiency) as well as community involvement (e.g., employee turnover and leadership diversity [4]. In order to meet their important criteria, those who do not have enough are compelled to accept short-term decisions that often have unfavourable long-term effects for the environment. Environmental problems caused by low consumption and poverty include chlorine fisheries, which threaten the reef ecology of poor fishermen in Southeast Asia, farmers in Africa burning trees for rice bread, destroying forests, and increasing poverty and deprivation by intensifying erosion and soil degradation [5]. Because of improved production technology used to meet expanding consumer demands, manufacturing activities have grown more important to the global environment. The growth of technology has resulted in environmental, air, and water degradation, ozone layer thinning, and a decline in green area. However, in response to these challenges, a sensitive public opinion has emerged, particularly in industrialized countries. New safeguards have started to be taken, both to sustain industrialization and to improve the environment [6]. Changes in the textile sector, as well as many other industries, have contributed significantly to the rise of environmental challenges in recent years, in tandem with technical improvements. The discharge of significant volumes of chemical loads into the receiving environment is the textile industry's main environmental impact. High chemical and water usage, energy consumption, air pollution, solid waste generation, and odor production are all important considerations. The drugs used in the cultivation of natural fibers and the emissions produced during the creation of synthetic fibers are at the root of the textile and garment industry's environmental issues. To treat the fibers, a number of processes requiring thousands of different chemicals, tons of water, and a large quantity of energy are required. The environmental problems that textile has caused have been reviewed in this review study, and solutions within the range of sustainability have been suggested.

2. Textile Industry's Environmental Impacts

The major environmental effects of the textile industry include the discharge of large amounts of chemical loads due to the high consumption of water and harmful chemicals used in this industry. The corresponding water pollution, energy requirements in production processes and knowledge air emissions, packaging and waste management production issues, and the formation of toxic fumes caused by bleaching, dyeing, and printing procedures [7]. The textile industry is responsible for some of the world's most severe economic and environmental effects. The worldwide textile sector (which includes the garment and footwear industries) is expected to reach $2 trillion in annual sales by 2018 [8]. After losing its status as the world's second-largest garment exporter to Vietnam in 2020, Bangladesh regained it in 2021, earning $35.81 in export revenue. Bangladesh earned $35.81 billion in 2021, according to the Export Promotion Bureau (EPB), whereas Vietnam earned $32.75 billion, according to the General Statistics Office [9]. Bangladesh sacrificed its second-place ranking as a garment exporter to Vietnam in 2020, earning $27.47 billion versus $29.80 billion. Because of the magnitude of the market, the textile sector is one of the most significant polluters of the environment, using chemical ingredients and processes [10]. Toxic chemical wastes from textile manufacturing are discharged into water sources, generally untreated, causing long-term damage to the soil, water, and ecology (Geotextiles N.D.). In addition to the cultivation of raw materials, the textile industry has damaging consequences throughout the life cycle of textile products, including raw material production (e.g., fibers, yarns, and textiles), garment production (e.g., arrangement and packaged foods), and expenditure of constructed textile products (e.g., end consumption, reprocessing, and disregarding) [11]. Excessive quantities of water, fossil fuels, and electrical energy are required during textile production operations such as dyeing, printing, and finishing, in addition to chemical emission into water sources. Textile dyeing needs almost 2.27×10^{12} litres of freshwater each year, while the generation of virgin polyester for fabric necessitates about 70 million barrels of oil [12]. Fast fashion is a marketing method that enables for the quick manufacture of popular products in stores. According to a recent estimate, the worldwide fashion e-commerce market is predicted to increase at a compound annual growth rate (CAGR) of 21.6 percent from $549.55 billion in 2020 to $668.1 billion in 2021. The increase is primarily due to businesses resuming operations and adjusting to the new normal as they recover from the COVID-19 pandemic's effects [13]. Due to rapid product adaptability and poor quality, fast fashion has contributed to the formation of a non-eco-friendly discarded clothing culture, in which buyers discard items after wearing it once or twice. This clothing culture has an impact on the amount of waste that ends up in landfills throughout the world [14].

3. Textile Industry Utilization and Manufacture that is Environmentally Sustainable

As a result of the textile industry's significant environmental consequences, sustainable development has become a key problem for textile producers' operations, as well as customers' lifestyles and product purchasing decisions [15]. As a result, textile organizations should implement incentives to strengthen their constituents (such as ownership, logistics providers, and stores) to participate in eco-friendly fashion activities [16]. Corporate social responsibility (CSR), green supply chain management (GSCM), and eco-design are the three types of environmental sustainability initiatives used by textile companies.

3.1 Corporate Social Responsibility (CSR)

CSR (Corporate Social Responsibility) is a self-regulatory corporate model which allows a company to be socially accountable to itself, its customers, and the broader population. Companies can be conscious of the impact on all areas of society, including economy growth, social, and environmental, by contributing to social responsibility, also known as corporate citizenship. Corporate social responsibility, also referred to as corporate citizenship, refers to a company's decision to operate in ways that benefit society and the environment rather than damaging them in the regular course of business. The fundamental environmental goal of CSR is to protect the environment, with a focus on carbon footprint reduction. Currently, the textile industry is the largest consumer a fifth of all chemicals produced by all industries globally. As a result, the textile industry accounts for more than 10% of global carbon emissions, and toxic gases such as N_2O, which is 300 times more harmful to the environment than CO_2, are generated as a result of low-cost synthetic fiber production's [17]. Corporate Social Responsibility urges textile firms to devote their resources and finances to environmentally friendly business operations in order to reduce carbon emissions [18]. CSR seems to have a lot of benefits for companies, according to Epstein-Reeves, including (a) creativity, (b) cost reductions, (c) trademark individuality, and (d) long-term planning [19]. For starters, commercial R&D efforts could result in game-changing products with environmental sustainability at their core (for example, Unilever's water-saving air conditioner) [20]. Second, CSR lets corporations to save money by minimizing packaging and energy use (for example, Levi's Water for customers and employees) [21].

3.2 Green Supply Chain Management in the Textile Industry

Green Supply Chain Management (GSCM) strives to reduce environmental damage caused by industrial operations, thereby incorporating environmental concerns into supply chain management. Academics and practitioners alike have embraced the GSCM. The construction of a green supply chain has gained a lot of traction, and businesses in the textile sector are focusing more on increasing the visibility, efficiency, and cost-cutting of their supply chains [22]. Consumers are becoming more environmentally conscientious of the things they buy as awareness of environmental concerns and global warming grows [23]. Supply chains are created with the goal of achieving long-term competitive advantages for all parties involved. Manufacturing companies have been urged to "green" their supply chains as a result of social and political concerns about environmental issue [24]. Green production companies set up systems for suppliers or subcontractors to buy environmentally friendly products and then follow basic principles to reduce waste and improve operational efficiencies throughout their supply chains, resulting in increased monetary and environmental efficiency [25]. To maintain administrative consistency of their business operations, green manufacturing businesses frequently support their supply chain partners in building an environmental management system (EMS) using ISO 14000 techniques in order to attain ISO 14001 certification. The EMS can be used to discover alternative mechanisms and opportunities for managing environmental repercussions effectively. Overall, green manufacturing firms may need to help their supply chain partners acquire environmental management skills by providing training projects and sharing their green experience [26]. In order to address current environmental issues in the textile industry, it is necessary that both manufacturers and other stakeholders (e.g., supply chain, marketing director, and consumers) are aware of their increased duties in the textile product life cycle, such as creating, using, and disposing [27].

3.3 Eco-design

Eco-design means creating goods and services that meet your customers' needs while using the least amount of resources and having the least impact on the environment and society [28]. Codesign is the process of developing or designing goods, activities, procedures, or organizations with the purpose of reducing or eliminating environmental, societal, or economic harm. Eco-design includes things like sustainable flooring, green energy heating systems, eco-friendly packaging, and even recyclable products. Ten essential environmental factors lie at the heart of eco-design [29]. Utilizing things that have a lower environmental impact results in less pollution and waste by using fewer materials in the whole production process, as well as less resources within the manufacturing process [30]. Reducing the environmental influence on product delivery by ensuring that items consume less resources to make less waste and pollution when used by end users. When in use, product function is optimized and the most effective service life is ensured, making recycling and reuse easier and minimize the environmental impact of disposal [31]. Eco-design is one of the most important commitments made by textile sector during product design, the important first step of the product life cycle, to achieve environmental sustainability [32]. H&M, Stella McCartney, and the Council of Fashion Designers of America, among many others, have lately launched large campaigns campaigning for environmental approaches in the fashion industry (CFDA). As part of its aim to be "climate positive" throughout its supply chain by 2040, the H&M group has announced a historic vow to employ 100 percent recycled or sustainable-source materials in its goods by 2030 [33]. According to the life cycle approach, eco-design can be implemented at several stages of environmental sustainability, comprising resource, processing, packaging, shipping, utilization, and disposal (United Nations Environmental Programme, N.D.). According to previous research, eco-design techniques have two crucial components: (a) Material selection and (b) Manufacturing process.

3.3.1 Material Selection

In the material phase, selection of materials refers to the use of biodegradable environmental assets and manufacturing methods without the use of toxic insects or fertilization [34]. These natural materials must meet environmental standards in both their properties and procedures (e.g., energy usage, material compositions, and disposal) to be suitable for eco-design (United Nations Environmental Programme, N.D.) [35]. To be appropriate for eco-design, these natural materials must meet sustainability targets in both their qualities and methods (e.g., energy usage, material compositions, and disposal) (United Nations Environmental Programme, N.D.). Cotton, flax, hemp, mulberry, and ramie are some of the most popular natural fibers used in the fashion business. Organic natural fibres meet environmental standards for composition and biodegradability, and they provide good technical performance (e.g., air conditioning, resistance to water, and cool buildings) and properties (e.g., anti - microbial, moisture wicking skills, and antiatopic properties) than synthetic fibers [36].

3.3.2 Manufacturing Processes

Designers may utilize textile science to create new types of eco-friendly materials by integrating natural materials, technologies, and knowledge into efficient technologies instead of using harmful chemical technologies in production [37]. Textile science for clothes is an innovative approach that employs direct correlation and physiological relationships from natural materials and techniques to create rich, unique, and individualized experiences (Van der. Mulberry fiber was mixed with titania nanorods (a natural photocatalytic material) to develop the concept of anti-yellowing and antibacterial textile [38]. The selected material and design of the product have an impact on the environmental impact of a manufacturing process. This is because the quantity of carbon emitted in consuming electrical energy for a manufacturing process is directly related to the amount of carbon emitted in the manufacturing process. The growing global population has increased demand for manufacturing commodities [39]. More pollution has resulted because of the increased productivity. A rise in production is positive from a manufacturing standpoint since it lowers manufacturing costs; nevertheless, an increase in energy consumption leads to an increase in carbon dioxide emissions, which is bad for the environment. Consumption-driven energy generation is a major contributor to carbon dioxide emissions and climate change. As a result of this issue, a community-wide awareness campaign to minimize pollution and promote more sustainable production has been planned [40]. Sustainable manufacturing is a method of enhancing environmental performance in the manufacturing process. Sustainable production refers to items that are planned, manufactured, distributed, used, and disposed of with low (or no) environmental and occupational health risks, as well as little resource use (materials and energy). This strategy is primarily motivated by fast growing issues such as environmental harm, massive volumes of waste, occupational health issues, and increased usage of non-renewable resources [41].

4. Five Ways Textile Manufacturers Can Reduce Their Environmental Impact

The environmental impact of the textile industry has long been a source of debate, with everyone from concerned consumers to government officials offering suggestions on how to make substantial, beneficial improvements. Here are five ways that textile makers can help the industry advance [42].

4.1 Reducing the Usage of Harmful Processes is a Smart Idea

One strategy for textile companies to improve is to examine which procedures are the most harmful to the environment and look for ways to change or eliminate them. Aalto University researchers developed a non-toxic way for producing waterproof, breathable textiles. It entails applying a carnauba wax covering [43]. The team also discovered that textile manufacturers could dye and waterproof materials at the same time using their technology. This technique's multitasking component could help the environment by minimizing the number of resources used during production**.** Instead of changing the production process, there are other options for reducing pollution, including: (1) the use of new, less polluting technologies; (2) effective treatment of effluent to meet specified discharge requirements using conventional and novel techniques such as electro-oxidation, coagulation-flocculation, biological treatment, photochemical processing, ion-exchange, and a variety of membrane techniques; and (3) recycling waste several time [44].

4.2 Research into Several Ways to Make Recycled Textiles

To reduce their environmental impact, a rising number of textile enterprises have turned to recycled materials. Nylon is made from recycled fishing nets by one company, while post-consumer cotton and polyester are the focus of another. The first cloth created wholly in a laboratory was nylon. It was employed for military products and as a silk substitute for items like stockings when it initially became accessible around World War II. Because of its durability and beneficial stretch qualities, it's now more frequently used in athletics, swimming, and other technical performance apparel. Textile Interchange, as an organization, assists the apparel and textiles industry in making the transition to more environmentally friendly materials that are better for people and the environment than traditional materials. Bio-based nylons (made from renewable raw materials) have the potential to be a viable replacement to virgin nylon. Recycled nylon is typically created from pre-consumer fabric waste, but it can also come from post-consumer sources like industrial fishing nets. The Recycled Claim Standard (RCS), the Global Recycled Standard (GRS), and SCS Recycled Content are all "chain of custody" standards that monitor recycled nylon through the supply chain [45]. Waste isn't going away, and these forward-thinking companies want to use it to create new products. Recycling benefits the environment in more ways than just textiles. Some companies claim that their textile-processing methods save 98 percent of water while reducing carbon dioxide emissions by 90 percent [46]. These new textiles are not yet widely available, but once consumers are aware of their existence, they may become more popular. Many environmentally concerned shoppers want to help the Earth by wearing eco-friendly clothing, and this is one method to do it.

4.3 Stop Following the Rapid Fashion Trend

The rise of fast-fashion refers to clothing that textile manufacturers produce in a hurry to keep up with ever-changing customer trends. There's also a trend away from long-lasting apparel. Many fast-fashion retailers anticipate that customers will only wear their clothes a few times before discarding them [47]. Because of the brief cycle, there is no need to focus on high-quality, long-lasting items. Consider this: traditional clothing has two cycles every year, whereas fast fashion has 50. For each week of the year, that's virtually a new cycle. People are buying more clothes but wearing them less frequently because of this trend. Textile companies might make a sincere attempt to avoid the fast-fashion trend Many enterprises in the United States and internationally sell ethically sourced clothing that stands in opposition to fast fashion's trash mentality. Made-to-measure and customized clothing can help to mitigate the problems connected with "rapid fashion" while also benefiting the garment business. Because of the high-quality materials, great craftsmanship, and precise fit, a custom or made to measure clothing is more likely to be used for longer. Extending the lifecycle of a garment minimizes the amount of unwanted clothing that ends up in landfill by preventing it from being discarded after one use. The fabric is cut to order, ensuring that there is no excess stock stored by a retailer at the end of each season, which is then significantly discounted to clear it swiftly [48]. More and more fashion brands are considering their production's environmental and social impact. Sustainable brands, on the other hand, will not necessarily be more expensive than brand-name clothing, for which consumers often pay a premium for the image but rarely for the quality or sustainability. The environmental impact of washing clothing garments is enormous. Every year, the average family does over 400 loads of laundry and uses roughly 60,000 litres of water. Heating the water for washing and running the drying cycle both use a lot of energy [49].

4.4 Upgrade Wastewater Management Procedures

The textile business generates a significant amount of effluent, particularly during the coloring and finishing processes involved with apparel. Consider that the industry consumes approximately 100 to 200 liters of water for every kilogram of the finished product [50]. Recycling wastewater is one option. A membrane bioreactor and reverse osmosis were utilized in one project in a Pakistani textile plant to do this, making the water suitable for reuse during cloth cleaning [51]. Another option is to remove pollutants such as dyes from wastewater before it leaves the facility and contributes to pollution. A PhD student recently investigated different approaches to accomplishing that goal [52]. Her studies cleansed the wastewater while consuming less energy and using fewer chemicals. Many of the solutions aren't yet ready for general usage, but textile makers should stay on top of developments and be ready to embrace them as soon as they become available. One of the most difficult aspects of wastewater treatment is selecting what to do with the sludge produced. When compared to standard wastewater treatment systems, solar photocatalytic wastewater treatment can reduce sludge by over 80%. Thermal hydrolysis technology has three applications: wastewater treatment, waste by-product reduction, and biogas production. Large amounts of sludge created during the industrial wastewater treatment process must be dealt with in traditional wastewater treatment plants. Thermal hydrolysis facilities, on the other hand, consider sludge to be a valuable source of energy rather than a waste. The production of biogas begins after the wastewater has been treated and the sludge has been collected. In enormous vats, the sludge is heated and compressed. Temperatures of 160 to 165 degrees Celsius are required, with pressures ranging from high pressure (7 – 11 or 12 bars) [53]. Batch or biothelys and Exelyis are the two types of thermal hydrolysis. Because of a microbial decomposition – oxidation – process known as "solar irradiation", sludge, also known as "organic content", is drastically decreased by a photocatalytic system. Solar irradiation has a synergetic effect that reduces the quantity of carbon in the sludge when paired with hydrogen peroxide – carbon being the principal ingredient in organic material.

4.5 Manufacture Fabrics that are Less Likely to Shed

Manufacturers of textiles can also benefit the environment by designing fabrics that are less likely to shed plastic microfibers during the washing process. One of the key causes for the release of such particles, according to a research team, is the amount of water utilized during a wash cycle. According to their findings, a delicate wash cycle lost 800,000 more fibers than a conventional wash cycle. As a result, our oceans are becoming more polluted with plastic. Microplastics are often carried out to sea because at-home laundry machines lack the extensive filters needed to effectively remove microplastics from wastewater. According to scientists, these particles are now found everywhere in the ecosystem, from deep seas in the Pacific and Atlantic oceans to Australia's beautiful beaches. The fibers may be particularly hazardous to marine species, which has had a significant influence on the food chain. Microplastics have been discovered in most of the marine creatures we monitor, including turtles, seals, and dolphins. Professor Tamara Galloway, an ecotoxicologist at the University of Exeter, told the Guardian that microfibers are the most common sort of microplastic [54]. "While humans can't be certain of the health effects of swallowing microfibers from textiles, humans can speculate." The recycled water can result in significant cost savings, particularly in terms of water, energy, and chemical usage. Before water is removed for treatment to eliminate leftover chemicals and other effluents created, wastewater is recycled in process baths and rinsing waters. Because steam condensate and cooling water are pure, they are easily recovered. Their thermal energy can quickly recoup the cost of the purchase [55]. However, this new research suggests that delicate cycles amplify the unfavourable effect.

5. In the Ready Mate Garment Industry, Ensuring Environmental Sustainability is a Responsibility

A sustainable manufacturing framework is essential to ensure sustainable development for green earth. The methods given below can be used to do this [56].

5.1 Resources Efficiency

Energy efficiency Reducing energy usage

Maximize alternative energy resources Water efficiency

Reducing water usage

Maximize alternative water supply

Material efficiency

Optimizing material flow and usage

Manage inventory and procurement

5.1.1 Energy Efficiency Reducing Energy Usage

The energy efficiency implies using less energy to do the same work, i.e., eliminating energy waste. Energy efficiency has several advantages, including lowering household and overall expenditures, as well as reducing greenhouse gas emissions and demand for energy imports. While renewable energy technology can assist achieve these goals, improving energy efficiency is the most cost-effective – and often the most rapid – option to cut fossil fuel use. Every sector of the economy, including buildings, transportation, manufacturing, and energy generation, offers significant opportunity for efficiency improvements [57].

5.1.2 Maximize Alternative Energy Resources Water Efficiency

The feasibility of removing four commercial reactive wool dyes from industrial wastewaters was investigated to address stresses on water resources sustainability management, water quality parameters of lake water induced by climate change, rainwater harvesting, and drainage water salinity and quality [58]. With major geographical disparities in DO decreasing, the risk of oxygen depletion was clearly anticipated. A longer residence duration is projected, accompanied with rising phosphate and chlorophyll a level and falling nitrate levels.

5.1.3 Reducing Water Usage

Growing populations, changing socioeconomic situations, and climate change are all contributing to the scarcity of water as a natural resource. Furthermore, water demand is predicted to climb further in some areas because of electrification with newbuild thermal power plants, and much more so if electricity generation is decarbonized with a large contribution of carbon capture and storage technology in fossil-fuel-fired plants. To keep the increased water abstraction and consumption of CCS power plants to a minimum, novel engineering solutions are required [59].

5.1.4 Maximize Alternative Water Supply

Water is used extensively in the production of electricity at thermal power plants, primarily for the condensation of steam in the steam turbines' condensers. Water diverted from surface or ground water sources such as rivers, tidal estuaries, and beaches provides most of the cooling capacity. Water abstraction is the term used to describe this process. Water abstractions for electricity production can account for up to 40% of total water abstraction from fresh water sources in developed countries [60]. Because of growing populations, changing socioeconomic situations, and climate change, water is becoming a scarce natural resource, and freshwater and marine environments are under increasing strain. Furthermore, water demand is predicted to climb further in some areas because of electrification with new-build thermal power plants, and much more so if electricity generation is decarbonized with a large contribution of carbon capture and storage technology in fossil-fuel-fired plants.

5.1.5 Material Efficiency

Materials manufacturing consumes a lot of energy and produces a lot of greenhouse gas (GHG) emissions, accounting for around a quarter of all human CO_2 emissions. It generates significant amounts of waste both during manufacture and at the end of its useful life [61]. More efficient material use could help to achieve a variety of environmental and economic benefits. Material efficiency comprises the development of technical methods, economic models, consumer preferences, and legislative instruments that would result in a significant reduction in the number of new materials needed to supply well-being.

Even though many opportunities exist, material efficiency is not utilized to its full potential in practice.

5.1.6 Optimizing Material Fow and Usage

The material flow analysis (MFA) depicts the entire movement of trash and the techniques for managing it. MFA, for example, provides transfer factors for all residue processes in various entities that can be used in LCA calculations. MFA can be utilized as the foundation for creating an input-dependent waste management model utilizing LCAs. Knowing the transfer coefficients for all treatments allows for the creation of process inventories for arranging and reusing in accordance with the MFA and guarantees that the mass balance in the framework is maintained. MFA entails a thorough examination of the content input and output flows into space over a set period [62].

5.1.7 Manage Inventory and Procurement

Sustainable inventory management (SIM) refers to inventory, warehousing, and material handling decisions that are made with the goal of decreasing environmental and social impacts while maintaining profitability. Modeling location and transportation concerns could result in more sustainable supply chains (SCs) [63]. Recent research has highlighted the necessity to consider elements other than standard inventory models when designing sustainable inventory systems, such as including environmental factors into the traditional economic order quantity (EOQ) model. It is critical to create a SIM model that considers income growth, waste prevention, and energy cost reduction. Emissions and costs are influenced by decisions on lead periods, replenishment quantities, and storage facilities.

5.2 Emissions Reduction

The following efforts must be taken to reduce emissions.

- Control and reduce the flow of the environment.
- Establish a recycling system and put it into action.
- Items should be managed, maintained, processed, and dealt with properly.
- Minimize wastewater and land degradation.
- It is necessary to account for carbon dioxide emissions.
- Reduce your carbon footprint.

5.3 Increasing Managerial Effectiveness

Establishing an effective environmental management system, improving accounting and environmentally monitoring performance, and compliance with environmental

Textiles go through several stages of manufacture, including yarn production, fabric development, wet processing, and textile fabrication [66]. This textile manufacturing process comprises "wet methods", which result in the generation of volatile organic compounds (VOCs). VOCs are measured in milligrams of carbon per cubic metre (mg/m^3) and vary from 10 mg/m^3 to 350 mg/m^3. In the industrial sector, process wastewater is a major cause of pollution. Per tonne of wool produced, 544 m^3 of effluent is produced, which is contaminated with bacteria, chemicals, dyes, and bleaches. The effluent is usually alkaline (high pH), includes particles, oil, and potentially toxic organics such phenols from dyeing and halogenated organics from whitening, as well as a high BOD/COD load. Heavy metals like copper and chromium may be present in dye wastewaters, which are frequently brilliantly colored. During the manufacture of wool, bacteria and other diseases may be released [67]. Wool is the most reusable and recyclable fiber among the major garment fibers. Wool's environmental credentials are bolstered by its extended service life and ability to be recycled into new textiles for garments, durable upholstery, or goods that rely on its natural fire and temperature resistance [68]. Wool can be utilized in industrial applications such as thermal and acoustic insulation, as well as pads to absorb oil spills, in addition to premium next-to-skin garments. Natural fibers, such as wool, lessen the textile industry's pollution and landfill build-up at the disposal stage. Wool biodegrades rapidly in warm, wet environments, such as soil, through the activity of fungi and bacteria to necessary elements (i.e. Nitrogen and Sulphur). Innovative cost-competitive processes for new soft handle contact, no shrinking, and washable woollen textiles are needed in the textile and garment industries. The most effective methods for fiber modification are oxidative or reductive procedures, as well as the application of polymer resins to the wool surface. However, such methods produce hazardous chemicals that can be retained in fabrics and industrial effluents. Proteolytic enzymes have been employed to generate environmentally friendly alternative procedures for fabric manufacture [69]. Because the enzymes employed are created from bacterial or fungal species cultivated via bioengineering fermentation methods and then extracted, the economics of enzyme production and extraction are cost-effective. However, using pure enzymes during processing is difficult to manage and may result in enzyme penetration into the body. Synergistic effects, which occur when two or more substances work together to produce effects that are greater than the sum of their parts, are the most significant environmental impact of rapid pH variation in the large body of water. This process is particularly important in surface waters, where an increase in pH increases the toxicity of chemicals such as ammonia and iron, posing serious risks to fish stocks and children washing and playing in the water.

6.1 The Cost of the Environment in the Garment Supply Chain

The garment sector has several environmental consequences. It pollutes the environment in a variety of ways. Environmental pollution includes wastewater discharge, pollution and waste discharge, air pollutants, and troublemakers [70]. Figure 3 denotes the impact of green supply chain management. The supply chain expenditures have an impact on the environment since delivering products more efficiently reduces your carbon footprint. Companies are now establishing sustainability initiatives to aid the environment by reducing miles travelled, production expenses, product waste, and unscheduled activities [71]. Importers and exporters work together with their suppliers to express their sustainability ideals and expectations. Many businesses, such as retailers and large brands in the United States, have begun to assess their suppliers' environmental performance. They assess their greenhouse gas emissions, energy and water use, and trash generation through surveys and questionnaires [72]. This information is used to determine what changes a corporation should undertake to reduce environmental

Figure 1. The diagram of textiles raw materials

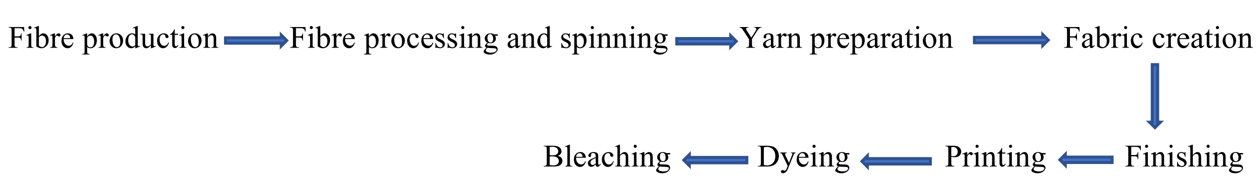

Figure 2. The diagram of production process

damage. Companies who are committed to sustainability will collaborate with their suppliers to identify pollution and waste sources and devise preventative solutions. To avoid pollution, they would also urge suppliers to employ cleaner and more cost-effective methods of production. The idea is to broaden the scope of accountability throughout the supply chain. Being environmentally conscious has other benefits besides making the world a greener place. Companies that strive for sustainability have a few benefits, including a better public image, a lower risk of noncompliance, the attraction of more environmentally conscious customers (a group that is rising), increased productivity and quality, and an increase in more sustainable products. According to Mohammad Momower Hossain, the environmental impact of textiles and the garment supply chain is as follows [73].

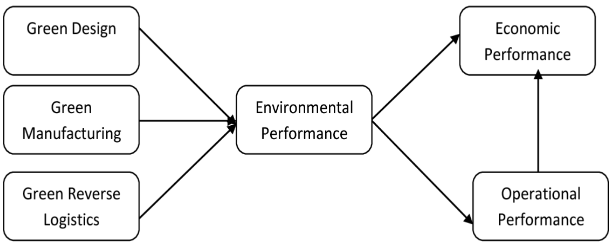

Figure 3. Impact of green supply chain management [74]

6.2 The Importance of Sustainability in Supply Chain Management

The concept of incorporating sustainable environmental operations into the traditional supply chain is referred to as "green supply chain management" (GSCM). Product design, material sourcing and selection, manufacturing and production, operation, and end-of-life management are all examples of this. GSCM emphasizes promoting value creation throughout the supply chain organizations to lower total environmental effect, rather than simply aiming to mitigate the supply chain's environmental impact [75]. Understanding the green supply chain management, social, and economic impact, as well as making appropriate changes to reduce it, is the foundation of sustainable supply chain management. Everything from the electricity system in a warehouse to product delivery and beyond can be included in the operation [76]. If your warehouse produces goods, your sustainability strategy will entail a study of the full manufacturing process, including the sustainability practices of all raw material suppliers, product assembly in the plant, and waste disposal and recycling. In a supply chain, sustainability is more than just becoming green. Because environmental responsibility is such a hot topic in today's business world, a supply chain built on a sustainable platform opens additional partnership opportunities. Practicing environmental in all facets of your business increases your credibility and reputation. A long-term supply chain can also help you boost production while lowering costs. By utilizing sustainable approaches and resources, organizations may enhance the efficiency of buildings, transportation, and machines while saving money. Tsunamis, devastating hurricanes, out-of-control wildfires, and other natural disasters are becoming more common because of global warming and climate change. CO_2 emissions from vehicles, ships, and factories play a significant role in this. Now that governments are taking aggressive measures to prevent climate change, freight businesses must adhere to new criteria that establish permissible emission levels from their fleet. By improving the effectiveness of your logistics management system and strengthening your supply chain, you not only minimize your carbon footprint, but you also boost your profitability [77]. As you demonstrate your green credentials, a sustainable supply chain might help you land more business. Internationally recognized standards, such as ISO 14001, can help you out even more. ISO 14001 is a management system that helps you find holes in your organization where you may achieve green efficiency savings. It's frequently a requirement in commercial tenders. With an accreditation to back up your environmental efforts, you can demonstrate to potential clients that you're making important steps to lessen your environmental effect. If the company examines its supply chain and can adjust, the benefits are numerous. Positive action can result in significant cost savings and improved margins, as well as a reduction in the environmental damage [78].

7. A New Business Model for Environmentally Sustainable Development

Sustainable development was once thought to mean social and economic progress that was also environmentally friendly. Since the introduction of the "three pillars" idea, it has increasingly become recognized that economic and social sustainability have benefits of their own, as well as specific and definite meaning as a component of human, social, political, and economic growth. In light of this knowledge, it is vital to examine the third pillar attentively in order to focus on the notion of environmental sustainability [79]. Environmental sustainability is important in the global textile industry during the retailing phase. Fashion retailers must develop a new innovative business model that includes the employee and the company, as well as measurement standards for measuring and tracking the company's environmental sustainability practices such as:

Clinton N.D., Amazon, Apple, Nike, Samsung, Dell, Lenovo etc. As a firm's future growth and success strategy, a creative business model aiming at environmental, social, economic, and technological challenges is gaining popularity (Clinton N.D.) [80]. Greentailing, also known as eco-tailing, is one of the most prominent business concepts dedicated to environmental sustainability.

7.1 The Retail Industry's Key Market Trends

In today's retail industry, several significant market trends are influencing retailers' performance and long-term growth: (a) greentailing, (b) demographic shifts, (c) experiential marketing growth, (d) thinking outside the box, and (e) offering services rather than goods [81]. To begin, greentailing is a business strategy that emphasizes environmentally conscious, socially responsible, and economically successful retailing in all aspects of the business [82]. The impact on retailers' environmental and societal commitments, consumer understanding and behavior, employees and the supply chain, and shareholder profits are all considered. Greentailing satisfies the growing demand among customers for organic, environmentally, and socially sustainable, and well-being products [83]. To meet these needs, greentailing requires the supply chain and retailers to be able to accept new ideas and generate money while adhering to ecologically friendly standards across the board. Greentailers with a main focus on greentailing increase faster than competitors with increased product innovation capabilities regarding environmental sustainability [84]. For example, two of the biggest greentailers, Walmart and Whole Foods, continue to grow at a far quicker rate than their non-greentailer competitors, thanks to constant green evolutions. Second, market dynamics have changed greatly from five years ago due to the significant changes in consumer demography [85]. Third, regarding product pricing, the in-store experience and consumer engagement with the brand are now important sales and profit drivers). Fourth, companies must think outside the box to come up with fresh and unique ways to connect with customers, especially non-traditional customers (such as online shoppers). Finally, rather than merely buying items, today's buyers demand service throughout their shopping trips. Today's retail sector depends heavily on the ability to manipulate customers. As a result, in today's retail climate, retailers must be aware of any factors that may impact customers' decisions in light of these major market trend alterations. Retailers should make ongoing attempts to link to their target customers' demands through innovative product merchandising, marketing, and packaging approaches in order to create a lasting impression on them. As a result, greentailing initiatives are critical current store growth drivers.

7.2 Greentailing

Greentailing is a movement toward more conscious retailing that is achieved by environmentally friendly activities and processes, as well as the sale of environmentally friendly products and services, that become ingrained in a company's corporate fiber [86]. In essence, companies who practice "green retailing", the two terms that make up the mash-up of "greentailing", are concerned with how their actions affect not just their customers, but also their employees, vendors, community, and environment**.** The retail industry is thriving in a familiar, demanding, and competitive environment. Green retailing can acquire a competitive advantage, according to Ferraro and Sands, because green enterprises have the potential to provide large returns on investment and cost reductions. Sinha discovered that sustainable practices are defined as "the business of selling environmentally friendly items to the general public and/or the practice of running a business that sells products to the general public using environmentally friendly ways [87]." Customer communication in greentailing, which spans stores, products, and people, is strongly influenced by corporate social responsibility (CSR). Greentailers must accordingly sell products that are organic and natural, free of dangerous ingredients, domestically grown and legally obtained through fair trade, and, most significantly, ecologically responsible [88]. Meanwhile, greentailers must give economic returns to their customers through environmentally and socially responsible business operations (e.g., supply chain, retailers, and staff). Academy Sports + Outdoors and Samsung C&T are two textile merchants who have dedicated to environmentally-responsible business practices. Both firms show how greentailing can promote an image of a company while also rewarding its shareholders economically [89]. Due to its commitment to complying with California's Proposition 65 and the California Transparency in Supply Chains Act (SB 657), Academy Sports + Outdoors, a Texas-based sports brand specialty retailer, is one of the leading greentailers. California's Proposition 65 has produced a list of over 850 toxic chemicals that are detrimental to people and the environment, and it prohibits their utilization in product manufacturing (Academy Sports + Outdoors N.D.). Samsung C&T, established in 1954, is a large global clothing design and retail firm with yearly sales over two billion dollars (USD). The company is a member of the Samsung Group and currently owns 50 44 K.E. Lee fashion brands (including imported, licensed, and private labels) [90]. In 2013, to mark Samsung C&T's 60th anniversary, the company opened the HEARTIST HOUSE, a CSR store based on the company's strong commitment to CSR. The name HEARTIST is a combination of the terms "heart" and "artist", and it represents the store's symbolic principles of environmental sensitivity, sharing, and donating.). The HEARTIST is designed for a purchase experience that is similar to giving, with five principles: reduce, reuse, recycle, refine, and recover. The HEARTIST is committed to environmental sustainability in five ways. To begin, the products in the store can be separated into three groups: The HEARTIST store of Samsung C&T in Seoul, South Korea. Textile Industry Environmental Sustainability (a) organic and natural-materials items, (b) donated clothing items from the company's leading luxury fashion brands (e.g., Bean Pole, Galaxy, Rogatis, Kuho, LeBeige), and (c) upcycled clothing items designed by young modern fashion designers who have offered their abilities. Second, the store's shopping bags are made of biodegradable, recycled plastic and are meant to be shared, allowing the customer to return to the store after filling them with items for donation [91]. Third, a warehouse built in the 1940s was converted into the main store using minimal synthetic materials. Fourth, recycled materials make up more than half of the store's fixtures. Fifth, the cooling water from the store's air conditioning system is recycled to irrigate the flower garden. Furthermore, personnel of the company, including fashion designers and merchandisers, volunteer to work as retail staff. Samsung C&T donates half of the proceeds from the HEARTIST store to charities and organizations that promote environmental sustainability through donations, campaigns, and events [92].

8. Make Use of Phases

Consumption of fashion products is influenced by the need for self-expression and identity creation. Because of a strong concern for the distinct personality created by fashion styles, as well as a lack of information about clothing's negative environmental effects, consumers are often less concerned about ethical or sustainable clothing use [93]. Rapid fashion and slow fashion are two separate trends that affect customer apparel purchasing behaviors in today's clothing market.

8.1 Rapid Fashion

Rapid fashion refers to an apparel company's business approach of successfully managing the supply chain in order to produce the most up-to-date trendy products in a timely manner in response to consumer demand. As a result, fast fashion's time-to-market (the amount of time it takes to produce a product from concept to final product) is only a few weeks, compared to the garment industry's standard six-month time-to-market [94]. For example, Topshop's time-to-market has been shortened to six to nine weeks, whereas H&M's has been shortened to three weeks. Aside from a time-to-market, another distinguishing quality of fast fashion shopping is the capacity to generate a wide range of clothing styles. Zara, the world's biggest fashion retailer, produces 12,000 styles per year from 40,000 different types made by 200 in-house designers. Fast fashion's features of providing the latest fashion styles at low prices in short turnaround times have resulted in a disposable clothing culture, in which consumers discard clothing after only a few uses; this utilization culture increases waste material amounts to be landfilled due to a shorter product life cycle. Fast fashion refers to low-cost, low-quality, mass-produced, and machine-made items that end up in landfills quickly. Slow fashion garments, on the other hand, are manufactured by hand, take time to produce, employ artistic skill, are of higher quality, and are more expensive. Over time, slow fashion clothing becomes naturally warm and pleasant. Years, if not a lifetime, can be spent on these. The utilization of organic, recycled, repurposed, and upcycled fibers is important to sustainable fashion. The materials used are those that use fewer chemicals, dyes, energy, resources, waste, and have a low environmental impact [95].

8.2 Slow Fashion

Consumers' environmental consciousness is expanding because of the increasing environmental repercussions of clothing use (particularly fast fashion), creating a need for sustainable clothes consumption through slow fashion goods. Eco-friendly apparel products enable consumers to make ethical and consumption decisions while also establishing an ecologically conscientious identity [96]. Slow fashion was first coined in 2008 by Kate Fletcher, is an alternative to fast fashion, according to, a sustainable design expert [97]. Slow fashion is clothing that is ageless, untouched by rapidly changing fashion trends, and lasts a long period. Slow fashion extends outside the use of organic compounds to include environmentally sustainable fashion methods based on customers' environmental awareness of textile items' effects across their whole life cycle [98]. Slow clothing brands prioritize product durability and reusability while designing clothing in an environmentally conscious manner. Slow fashion trends enable consumers to purchase timeless designs that will last a long time while retaining good product quality, and designers to develop seasonless sellable products on the market [99]. As these new slow fashion products appeal to consumers seeking distinctive designs with a willingness to pay a premium, slow fashion can reduce the textile industry's carbon footprint in subtle alternative ways without overloading environmental pressures solely on textile companies; thus, slow fashion can reduce the textile industry's carbon footprint in delicate alternative ways without overloading environmental pressures solely on textile companies. In the textile industry, Eileen Fisher is a famous example of a slow fashion brand, delivering timeless and ageless patterns by reproducing chosen icon styles through seasons while adapting to new trends for a broad consumer base.

8.3 Clothing Consumption in the Future

As the fashion industry grows in size, a large volume of clothing waste causes major environmental problems by needing more and more landfill space each year throughout the world. As a result, promoting environmental sustainability will necessitate a more holistic approach to influencing customers' apparel purchasing behavior to include concerns or obligations to the environment and society. To safeguard the environment, garment companies, like consumers, must rethink their green business practices in terms of how clothing is designed, manufactured, consumed, and disposed of. Consumers are increasingly conducting research on a product and the firm that manufactures it before making a final purchase [100]. Consumers are better educated than ever before, so they buy less but better. "Conscious consumerism" is the future's trend!

For a variety of reasons, impulse purchases have decreased during this pandemic. People are visiting physical stores in lower numbers than in the past. When we go to the mall to buy a pair of shoes, we wind up purchasing a dress and a pair of fashionable earrings as well.

8.4 Disposal Procedures

After consumers use textile products, used textile waste is commonly dumped (e.g., clothes, footwear, and accessories). More textile waste is produced every year around the world, especially in fashion centers like the United States and the United Kingdom. Textile production in the United States has gradually increased (for example, clothing, footwear, and accessories). In 1999, 8.25-billion-kilograms worth of textiles were manufactured. By 2009, this sum had increased by 11.55 billion kilograms, and it is expected to increase by 16.07 billion kilograms by 2019. (Council for Textile Recycling N.D.). According to 2009 textile output numbers of 11.55 billion kilogram, each US resident purchased around 37 kilograms of textile items per year, meaning that Americans now buy five times as much clothing as they did in 1980 [101]. After these textiles were used, only 3.8 billion pounds of textile garbage were given or recycled, accounting for 15% of total global landfill garbage; the other 9.53 billion kilogram of textile waste (85%) was landfilled (Cline 2014; Council for Textile Recycling N.D.). In the United Kingdom, like in the United States, 10% of the 1.4 million tons of old textile waste is estimated to be landfilled each year. Due to the massive amount of textile waste created each year, the UK's recycling and waste management sectors are experiencing concerns with future landfilling. Because of the growing interest in green clothing consumer movements, discarded used textile goods are now recognized as an economic value regenerator through reuse and recycling. When textile waste is recycled, for example, 45 percent of it can be worn as second-hand clothing, 30 percent can be cut up and made into industrial waste, 20 percent biodegrades after dumping, and only 5% is worthless. In general, municipal governments and trash management companies have a lot of money to make from these discarded products [102]. Customers benefit from recycling because it reduces the demand for new garment production, reduces manufacturing, which saves a lot of energy and raw materials, and reduces energy and raw materials, which results in fewer pollutants in the environment (Second Hand 4 Business Ltd. N.D.). As a result, consumers should be urged to recycle and donate their clothes to help the environment.

9. Conclusions

The textile manufacturing process requires a lot of resources, including water, fuel, and a variety of chemicals, over the course of a long production schedule that generates a lot of waste. Pollutants generated by the worldwide textile industry are wreaking havoc on the environment in unimaginable ways. It pollutes land, air, and water, rendering them ineffective and unproductive in the long term. Reducing the toxins released by the textile sector has become vital. Textile companies and their raw material processing units have contaminated the air, water, and land, posing a major threat to the environment. It has put the lives of humans and other animals on the planet in jeopardy. Environmentally friendly agricultural and manufacturing processes should be used. There is an immediate need to take action in this direction. Textile manufacturing has a negative impact on the environment due to frequent and relatively large GHG emissions, water withdrawal, the release of toxins into our ecosystem from pesticides and herbicides used in cotton production, and a variety of other factors. An eco-friendly product is one that is created, utilized, or disposed of in a way that greatly lessens the harm it would otherwise cause to the environment. In addition to reducing the environmental impact of textile manufacturing and making our world a better place to live, the use of such materials will help to minimize the harmful effects of toxic chemicals (pesticides, herbicides, and so on) on human health.

Author Contributions

Conceptualization and writing, M.T.I; supervising, R.J; reviewing, M.J; reviewing, M.S,H; editing R.I; formatting figures and manuscript editing; M.M.I; editing and reviewing; M.S.H; manuscript redesign, A.K; final reviewing and editing, A.H.R.

Conflict of Interest

All authors checked this work and declared no conflict of interest.

Funding

This paper received no external funding.

Acknowledgements

I would like to thank Tarekul Islam for his kind support to complete this work.

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Non-Metallic Material Science

https://ojs.bilpublishing.com/index.php/nmms

ARTICLE

Sustainability of Renewable Energy Systems with Special Reference to Ocean Thermal Energy Conversion Schemes

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ARTICLE INFO

Article history

Received: 22 August 2022

Revised : 7 September 2022

Accepted: 9 October 2022

Published Online: 20 October 2022

Keywords:

Sustainability

OTEC

SOTEC

Bio-fuel

GHG emission

Flora and fauna

Quality of life

Hydrogen

Commercial acceptability

ABSTRACT

It was required to determine relative merits of commonly used renewable energy (RE) systems for which estimation of their individual sustainability percent achievable was chosen as the single criterion assessment tool. The methodology developed for estimating sustainability included identification of individual sustainability indices (SI) and examining the scope of sustainability percent input /kWh power generation for each of SI indices and summing them up estimating total sustainability accrued from respective RE systems. The RE systems studied included photo-voltaic (PV) cells, bio-fuels, on-shore & off-shore wind energy and OTEC schemes. Coal power plant being commercially viable was studied as the referral energy scheme. Nine SI indices identified for study included resource potential, greenhouse gas saving, influence on flora & fauna, effects on human health, land loss aspects, food and potable water security, economy evaluation, and improvement in quality of life from economic growth. Total sustainability achievable showed the highest in OTEC, followed by wind, bio-fuels and PV, respectively. SI index on quality of life showed RE schemes like OTEC & bio-fuels competing equally with coal power plant having poor sustainability with the least power generation cost; whence Hybrid OTEC showed the highest sustainability with high power production cost. Four fold approaches have been suggested for reducing power generation cost of OTEC. (i) Adopting economically viable scheme of not less than 40 MW. (ii) Heating up the working fluid with solar irradiation, terming SOTEC scheme. (iii) Saving cable laying cost, from hydrogen production utilizing the power generated. (iv) Hybridization of OTEC scheme.

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DOI: https://doi.org/10.30564/nmms.v4i2.5023

1. Introduction

Energy use has been identified with economic development and simultaneous improvement in the quality of life, which has led to its ever increasing production. Since the resource for energy production is mostly fossil fuel-based (coal, oil and gas), such unabated energy production rate is causing fast depletion of fossil fuel resources which took millions of years for its formation. The fossil fuel reserve/production ration (R/P ratio) for coal with its present rate of consumption has been estimated to be of 119 years, while this ratio for combined oil and gas is hardly 60 years [1]. Besides such fuel depletion problem, the associated emission of greenhouse gases from fossil fuels (mostly from CO_2 emission) threatens global warming with serious consequences of sea level rise and other associated environmental hazards. It has been estimated that for complete combustion of 1 ton of coal-CO_2 production would be around 2.86 tons [2]. It is with these problems in view the world summit met in 2002 and agreed upon to gradually switch over to alternate type of Energy that would be environmentally sound as well as sustainable, having scope of replenishing post use [3].

In fact, sustainability has been stressed upon in the 96th Plenary Session of UN General Assembly who took up this issues as a global strategy, and defined it as "the developmental strategy, that would be able to meet the needs of the present without compromising the ability of future generations to meet their own needs, both in respect of energy and raw materials" [4]. The guiding principle underlying it spells out categorically that:

- "Each generation should require the diversity of resource base so that it does not unduly restrict the options available to future generations.
- Each generation should maintain the planet's overall qualities so that it does not get into a worse condition than received" [4].

It may be relevant to add that not only the cost component which is coming in the way of wider commercial acceptability of RE systems, each of them has their own specific advantages and disadvantages. For example wind energy though rather cheaper but have the limitation on availability of round the clock suited wind speed for power generation. Bio-fuels though advantageous for use as transport fuel, puts pressure on agricultural land. Photo-voltaic cells though advantageous in inaccessible areas, but require large areas for their installation. OTEC plants though assures non-stop round the clock power supply and have the scope of availability of huge by products, but incurs high capital cost-though have much scope of cost reduction with improved designs. It is thus considered useful to make their gradation using a single criterion assessment tool of their sustainability percent achievable per kWh power generation.

The methodology developed for ascertaining sustainability percent achievable per kWh power generation for each of these RE schemes. The following three fold approach was pursued.

(i) Identification of the individual sustainability indices (SI) required to be studied.
(ii) Scale development of sustainability gain from zero to 100. (could have negative value also on sustainability loss issues).
(iii) Logic of assigning suitable sustainability score value to each of the SI indices, where from total sustainability of the individual RE scheme can be made adding up the SI score values over each of the SI indices.

The RE schemes thus studied are as below.

1) Solar photo-voltaic cells (PV cell) which can generate electricity tapping the energy of solar insolation over the earth's surface.
2) Bio-fuels as can be produced from decomposition/degeneration of bio mass.
3) Taping wind energy of blowing wind.
4) Ocean Thermal Energy Conversion (OTEC) - generating electricity utilizing the temperature differential between surface ocean water (SOW) and deep sea ocean water (DOW).
5) Hybrid OTEC for examining scope of performance efficiency of OTEC schemes.

In order to meet the same it was required to spell out the individual sustainability indicators inclusive of environmental fall outs, termed as sustainability indices (SI), as well as developing the modus operandi of ascertaining total sustainability from combined effect of all the individual indices as may be accrued upon. Due weight-age values of the individual indices are also required to be assigned for each of the individual indices. Total sustainability can thus be estimated summing up the individual sustainability contribution from the identified indices, as applicable for concerned RE schemes and thereby making their ranking.

2. Identification of Sustainability Indices (SI) for Energy Systems

In 2015, the 70th session of UN General Assembly adopted 17 goals with the objective of sustainable and universal development programme with active participation of UNESCO, as shown below in Figure 1 [5].

Figure 1. Sustainable development goals of UNESCO [5].

Based on above stated issues, as well as considering the criterion for annulling the resource depletion problems and minimizing environmental hazards, besides ensuring issues like energy security, food & potable water availability relevant for RE systems in particular, the following sustainability indices (SI) could be identified for the present study. They are shown as below:

1) Scope of tapping concerned energy resource availability.
2) Scope of averting global warming from saving of GHG emission/carbon foot print..
3) Species (flora and fauna) loss or gain aspects from environmental fall outs.
4) Influence over human health from land, water or air pollution, if caused.
5) Land loss caused, if any.
6) Scope of availing food security.
7) Availability of potable water.
8) Economic viability which decides the commercial acceptability of the energy system.
9) Addressing scope of improving upon the quality of life, mainly from economic growth.

Quantification of each of these indices over the individual energy schemes, can be made based on the percentage of influence accrued from each of these indices. The summation of these values would then indicate the total percentage of sustainability achievable from the effect of all these indices put together. The values could of course be positive or negative depending on favouring sustainability or annulling it. If all these indices are positive showing maximum sustainability, the total sustainability would be 100 percent. If however, all of them show nil sustainability the result would be zero. In practical cases however it would be in between zero and 100 percent. Thus we get a scale of measuring sustainability percent for an energy system, which could serve as a single criterion assessment tool in ranking different energy systems and could be also be helpful in R & D efforts for their performance improvement.

3. Assessment Modality of SI for Different Energy Systems

An important point to be noted is the weight-age factor that is required to be assigned for each of these 9 SI indices, which would depend on their relative importance, and hence must not be the same for all. In 2019 in Malaysia the RE sources (solar PV, hydro--power & bio fuels) contributed to a meager 0.6%, of the total energy production, where coal contributed to 43% of the total energy use [6]. This suggests the commercial acceptability is an important point to be reckoned with urging higher weight-age factor for economy evaluation index. Same is with GHG emission aspect threatening global warming. Food and potable water availability are also considered important indicators as stressed upon from UNESCO indices shown in Figure 1. Land loss aspect would have low priority, being of local importance only. The percentage distribution of the above stated 9 SI indices is hence assigned as below in Table 1, summation of which makes 100 percent for the concerned energy system under study.

Table 1. Assigned sustainability percentage distribution of individual SI indices

Sustainability Index	Weight-age factor	% distribution	Remarks
Energy resource	1.0	10	Moderately high
Saving GHG emission	1.5	15	High
Flora and fauna	0.8	8	Moderate
Human health	0.8	8	Moderate
Land loss	0.5	5	Low
Food security	1.2	12	Rather high
Potable Water availability	1.0	10	Moderately high
Economy evaluation	1.6	16	High
Quality of life	1.6	16	High
Total		100	Summing up % share.

3.1 Energy Resource

PV cells: Direct tapping of solar energy is done using **PV cells**, which can generate electricity when light falls on them. Though this resource is almost inexhaustible, with annual electricity production capability of 1.5×10^{18} kWh from solar radiation (more than 23,000 times the energy used by human population globally [7]), but it has the limitation of non-availability at the required site during night, requiring array of battery backup as well inverters, electricity production from PV cells being DC.

For all practical purposes hardly 9~10 hours sunshine could be available for PV cells with around 30% energy loss [8]. Despite this limitation, PV cells have a unique advantage of its ease of installation in otherwise inaccessible areas. Thus sustainability criterion on resource aspect of PV cells can be considered to reach value around 70%, mainly for its easy installation in inaccessible areas as well.

Bio-fuels: Their resource gets restricted, as they are availed at the cost of agricultural land use for the growth of agricultural feedstock biomass. These are produced from plant wastes consisting of cellulose, hemicellulose or lignin type carbon-based compound, which are the primary resource for availing such energy type [8].

Though Sabah's oil palm plantations are a large source for biomass, but biomass has better value as feedstock in export markets rather than as a fuel source. This has led to the closure of biomass-based power bio-fuel plants in 2018 [9].

Thus resource sustainability index of bio-fuel cannot be considered to be not more than 50%.

Wind Energy (both off-shore & on-shore wind farms): The exploitable good cut in wind speed is around 3~5 m/s, but should not exceed 15 m/s [10,11].The scope of availability of wind resource with such optimum wind speed - for both on shore and off-shore schemes - are however limited which is not only site specific but also time specific with seasonal changes.

Thus on the count of resource sustainability index, the on-shore wind could reach maximum 30% and off-shore having better availability may be considered to reach a value of 50%.

OTEC: Around 10 TW (10 trillion W) of power, which is nearly equal to the present global energy demand, could be met only from the available OTEC resources, without affecting the thermal structure of the ocean [10]. Of course this heat input from radiant energy of the sun is maximum in equatorial region of the ocean surface which gradually lowers down, towards the polar zone. It has been estimated that 60 million sq. km. of tropical seas absorb solar radiant heat energy equivalent to 250 billion barrels of oil [11].

It may also be pointed out that due to high specific heat of water, ocean surface temperature does not meet any change during night time and exploitation of electricity from OTEC can be available 24*7 round the year with its capacity factor 95%.

Thus in all types of OTEC schemes resource sustainability index can be said to reach minimum value of 90%.

Coal based power plant: In order to compare sustainability of RE systems, a coal based power plant may be considered from resource depletion aspect taking time line to be of a millennium. In that case R/P ratio of coal with 119 years may be considered to attain hardly 12% sustainability.

Based on the above discussions, the sustainability on resource tapping aspect for all the energy systems is compared in Table 2 given below.

Table 2. Sustainability percent on resource index for the energy systems

Energy systems/ Sustainability	Sustainability% allotted for the resource index	Sustainability % of the energy systems	Sustainability % on its resource index share
PV solar	10	70	7
Bio-fuels	10	50	5
Wind on shore	10	30	3
Wind off-shore	10	50	5
CC-OTEC	10	90	9
Hybrid OTEC	10	90	9
Coal plant	10	12	1.2

3.2 Averting Global Warming by Restricting Green House Gases (GHG)

The greenhouse gases mainly responsible for global warming are CO_2, CH_4, NO_2. It may be relevant to add that though the global warming potential (GWP) of CO_2 = 1, which for CH_4=21, N_2O=320; but for all practical purposes the emission of CO_2 is of overriding importance because of its much higher emission rate in RE operations, compared to other gases [12].

Unlike fossil fuels, the scope of CO_2 emission in RE systems though virtually nil during their operational stage, but they may pose some environmental burden during their construction phase (being carried out using conventional fossil fuels). Hence, it becomes imperative to make life cycle analysis (LCA as per ISO 14040-14044 standard) of them, right from the extraction stage of the raw materials involved till their installation and dismantling, termed 'cradle to be grave operation' [13]. Emission of CO_2 thus estimated for RE systems operation, may then be compared with emission of CO_2 from a coal power plant for ascertaining its sustainability percent gain considering coal plants sustainability loss to be of 100%. Emission of CO_2 from LCA studies of a typical coal power plant has been reported to be of 900 g/kWh [14].

Sustainability percent of the RE system = CO_2 emission % saved/kWh, compared to coal plant.

A typical coal plant's CO_2 emission has been reported to be 900 g/kWh [14], and let the CO_2 emission from the concerned RE system estimated from LCA studies be = g_x/kWh.

In that case considering 900 g/kWh to be of 100% emission, g_x/kWh would be= g_x/kWh*100/900 percent emission = emission percentage/kWh of that RE system.

CO_2 emission percent saved/kWh from that RE system compared to coal would obviously be (100 - g_x/kWh*100/900), which is the sustainability percent/kWh of the concerned RE scheme for the SI of "GHG saved".

Solar PV: In case of solar PV CO_2 emission/kWh may vary between 23 and 44 g/kWh [15], the mean value of which around 30 g/kWh, is being considered for sustainability assessment in the present study. Thus sustainability percent of PV cell on this count would be:

100-30*100/900 = 96.7%

Bio-fuels: CO_2 emission/kWh of bio-fuels vary between 25 and 93g/kWh, depending on biomass feedstock used [18], the mean value of which around 60 g/kWh is considered in the present study, for assessing sustainability percent achievable.

Thus sustainability percent of bio-fuels on this count would be = 100-60*100/900 = 93.3%.

Wind energy: CO_2 emission/kWh has been said to be of 9.7 and 16.5 g/kWh for onshore and offshore wind energy systems, respectively [16,17].

Thus sustainability percent for on-shore wind energy would be = 100-9.7*100/900 = 98.9%.

And sustainability percent for off-shore wind energy would be = 100-16.5/100 = 98.2%

OTEC schemes: It could be shown from hypothetical case study of 100 MW OTEC, that CO_2 saving percent for a hybrid OTEC system would be more than 97 percent [20]. But it is to be taken note of that all types of OTEC plants can hugely increase oceans capacity of CO_2 consumption, from the burial of increased growth of marine bio-species, due to upwelling of deep ocean water, from increased growth of planktons, which is the food web of bio-species. This phenomenon, known as sequestering of CO_2 is analogous to plantation in land for annulling global warming, by increased capability of CO_2 dissolution in ocean.

Thus all types of OTEC plants can be considered to attain 100% GHG sustainability because of its inherent capability of increasing CO_2 dissolution saturation limit of the ocean water.

Based on the above discussions sustainability percent on aspect of averting global warning from GHG saving index has been shown below in Table 3.

3.3 Flora and Fauna

The influence of RE systems over different types of flora and fauna is required to be ascertained both from the qualitative aspect as also from quantitative aspect. The former could be both positive or negative, depending on whether it favours sustainability from species growth or annuls it from loss. The quantitative aspect, which means the extent of influence caused from different types of impacting parameters of the concerned energy systems, can be decided from their degree of influence as may be caused over the concerned flora and fauna. Obviously assignment of sustainability percentage could be made from

Table 3. Sustainability percent on scope of averting global warming for the energy systems.

Energy systems/ Sustainability	Sustainability% allotted for GHG saving index	Sustainability% of the energy systems	Sustainability % on its GHG saving index share
PV solar	15	96.7	14.5
Bio -fuels	15	93.3	14.0
Wind on shore	15	98.9	14.8
Wind off shore	15	98.2	14.7
CC- OTEC	15	100	15
Hybrid OTEC	15	100	15
Coal plant	15	0	0

closer examination of the impacting parameters, indicating categorization of high, moderate or low. Assignment of sustainability percent valuations can be made accordingly.

Solar PV: It is by and large environment friendly, having no impact on flora and fauna in its overall operations. But it also does not assist in growth of them, resulting in their sustainability percent to be nil.

Bio-fuels: Bio mass source favours growth of flora and fauna with no appreciable negative effect. Thus its influence being moderately high, it can be assigned a sustainability index of +60%.

Wind energy on-shore: The collision with its rotor blade and noise of wind energy have some negative effects over the birds and bats, though it is rather minor [21]. Thus overall sustainability on-shore wind may be assigned a value of –20%.

Wind energy off-shore: Noise during its construction phase may affect the roosting and preening on species growth, which can be annulled if this period is avoided for construction. In that case, sustainability index as may be assigned could be –10%, a little better than on-shore wind.

OTEC schemes: Upwelling of bottom layer ocean water with rich nutrients would favour growth of planktons - the food web of marine species and thereby can hugely facilitate growth of fish, sea -mammals and other marine species [22].

In fact, abundant production of shell fish could be observed in the west-coast of south America, due to upwelling of bottom layer ocean water from Humboldt current [23]. It was estimated that a 100 MW OTEC plant, from its upwelling of 136 m^3/sec nutrient laden bottom layer water would yield an annual production of 25,000 tons of shell fish [23].

However, there is a caution note that arises from some possibility of uplifting certain types of harmful planktons (HABs-harmful algal bloom) as well, depending on site and seasonal variations [24]; though upwelling of cold water simultaneously, help appreciably the overall growth of marine species [25].

Keeping the above perspective in view the sustainability on flora and fauna for all types of OTEC may be considered to be not be less than 70%.

Coal plant: Acidgas emission, particulate matters and heavy toxic metals like, Pb, As, Hg- pollutes air and water bodies in the vicinity of coal based power plants [26]. These factors affect negatively all types of flora and fauna of both of land and water bodies, though being not having direct effect can be said to be rather moderate. Thus sustainability percent on this index for coal plants may be considered to be around –50%.

Based on the above discussions sustainability percent on flora and fauna index has been shown below in Table 4.

3.4 Human Health

In ascertaining influence of RE systems over human health the same yardstick and methodology of qualitative and quantitative assessment for sustainability percentage estimation could be followed.

Solar PV: There remain a possibility of air and/water pollution affecting human health mainly from the toxic metals used in the construction of solar cells (containing gallium arsenide, copper-indium-gallium-diselenide, and cadmium-telluride, and others), as well from its array of batteries and other accessories, during their disposal stage and/or if not handled properly. Construction materials of solar cells inclusive of its accessories like the array of batteries, if not handled and disposed of properly, may pose environmental or public health threats to human health from water and soil pollution [27]. However, their effect would be marginal, the volume of such material being small and not affecting during their operational phase.

Thus, sustainability on the index of human health may be considered to be around –15%.

Bio-fuels: As such it has no effect on human health. But the human waste materials having the option of get-

Table 4. Sustainability percent on flora and fauna index for energy systems.

Energy systems/ Sustainability	Sustainability% allotted for flora and fauna index	Sustainability% of the energy systems	Sustainability % on its flora and fauna index share
PV solar	8	0	0
Bio -fuels	8	60	4.8
Wind on shore	8	–20	–1.6
Wind off shore	8	–10	–0.8
CC- OTEC	8	70	5.6
Hybrid OTEC	8	70	5.6
Coal plant	8	–50	–4

ting utilized as the resource material of bio-fuels, it can be said to have rather a positive impact in sustainability on human health index, which may be assigned a value of +25%.

Wind energy: Both on-shore and off-shore wind energy have no effect on human health, whose sustainability on this index may be valued as nil.

OTEC plants: It is not only enhancement of fish growth and other marine species growth, as explained in section 3.3, influence positively human health index of sustainability; but scope of availability of various types of weeds and pigments having medicinal utility in addition to mineral rich ocean bottom layer water are hugely advantageous for human health.

The sustainability of this index for all types of OTEC, may hence be considered to attain a value of +90%.

Coal plant: Air and water pollution caused from the slag wastes from coal plants, as well as from toxic metals, acid gases & particulate matters - may affect appreciably, various types of health problems, like asthma, COPD, cancer & several other diseases [27]. Thus sustainability from this index may be considered to attain a value –70%.

Based on the above discussions sustainability percent on human health index has been shown below in Table 5.

3.5 Land Loss

Land requirement, expressed as m^2/MWh, is an important parameter which involves cost component in power generation plants, and hence is an important parameter to be reckoned with. The scale of land requirement may be set using underground coal based power plant's land requirement to have near zero value, which is 0.2 m^2/MWh [28]. On the higher side, bio-fuels minimum land requirement of 250 m^2/MWh [28], may be set as 100, which would have 100% negative sustainability.

PV solar: It requires around 10 m^2 area per MWh power production [28]. Since roofs and terraces can also be utilized, effective land area requirement may be considered to be around 8 m^2/MWh.

Following the above scale presumed, sustainability percent of land requirement for solar PV would be 3.2%.

Bio-fuels: Its sustainability, as per discussions in section 3.5 would be 100%.

Wind on-shore: Its land requirement is reported to be 1.0 m^2/MWh [28]. Thus, as per the sustainability scale developed, it would have –0.4% sustainability.

Wind off-shore: Obviously with no land requirement its sustainability loss would be nil.

OTEC schemes: All OTEC schemes (other than land

Table 5. Sustainability percent on human health index for energy systems.

Energy systems/ Sustainability	Sustainability% allotted for human health index	Sustainability% of the energy systems	Sustainability % on its human health index share
PV solar	8	–15	–1.2
Bio-fuels	8	25	2
Wind on shore	8	0	0
Wind off shore	8	0	0
CC- OTEC	8	90	7.2
Hybrid OTEC	8	90	7.2
Coal plant	8	–70	–5.6

based ones) would have nil loss of this index.

Coal plants: Unlike coal plants land pressure with underground mined coals, land pressure in case of coal plant for opencast mined coal availability are high, having a value of 5 m^2/MWh. But with the current practice of open cast coal mining with the reclamation of the excavated soil with re-vegetation and soil reconstruction post-mining, would lower this land loss appreciably [30]. Thus for all practical purposes land pressure on coal plants in general can be considered to have a value of 2.5 m^2/MWh.

Thus with the scale developed sustainability of coal based power plants may be considered to have a value of 1%.

Based on the above discussions sustainability percent on land loss has been shown below in Table 6.

Food Security: All types of energy systems indirectly helps in food growth being used in agricultural farming/irrigation and/or aquaculture/ trawler fishing etc. However, it is only the OTEC technology which have direct bearing on food growth, with enhanced growth of marine bio-species, as per discussions made in section 3.3. Bio-fuels rather have deleterious effect being grown at the cost of agricultural land. However, sustainability assessment on food growth from different energy systems are discussed below.

Solar PV: The only advantage of PV cells in food growth is its scope of availability and utilization, in even the inaccessible areas, though as such it has no effect on food growth. Thus sustainability on this system would be marginal, though positive; the value of which may be assigned as 25%.

Bio-Fuels: Bio-fuels have rather negative impact since it thrives at the cost of agricultural land though its scope of use as transport fuel finds use in tractors/fishing trawlers etc., having mixed reaction of both helping its growth and at the same time reducing it.

Thus by and large its impact on sustainability may be assigned as zero, if not negative.

Wind energy: Both on-shore and off-shore wind energy when connected in grid line may be instrumental in marginally helping indirectly on irrigational efforts etc, making a minor positive impact on food growth, whose sustainability may be assigned as 15%.

OTEC: It has been estimated that annual growth of shell -fish meat from the utilization of nutrient laden DOW from a 100MW OTEC can be around 20,000 tons. It could also be estimated that implantation of 10,000 OTEC plants of 100 MW would be able to meet the entire annual protein requirement of 2 billion people with daily intake of 35 g/day [25].

In addition to it, DOW from OTEC may be utilized for food grain preservation in cold storages, without any requirement of electricity.

Thus sustainability for all types of OTEC schemes may be assigned a value of 90%.

Coal plant: Though cheaply available power from coal, may be indirectly helpful in food growth from irrigation etc. But it has negative impact from open cast mining of coal - which affects the agriculture friendly top soil (taking few 100 years for its formation) from its excavation. This makes a negative impact on food growth.

Thus, coal plant may be said to have zero sustainability on food growth, from cancelling out of both these marginal positive with marginal negative impacts.

Based on the above discussions sustainability percent on food growth has been shown below in Table 7.

Potable water availability: WHO guide line suggested the minimum requirement of potable water would be '2 liter/capita/day', whence 50 liter/capita/day is assigned as the optimum level of water use covering all purposes [32]. In the present study we are concerned only with the scope of potable water availability, which can be availed with a cost from necessary treatments. But except hybrid OTEC scheme (or OC-OTEC) all other energy systems have no scope of its availability, nor have any negative effect either. Thus other than hybrid OTEC all other energy systems would show zero sustainability on this index.

It has also been reported that even 1MW H-OTEC

Table 6. Sustainability percent on land loss index for the energy systems.

Energy systems/ Sustainability	Sustainability% allotted for land loss index	Sustainability% of the energy systems	Sustainability % on land loss index share
PV solar	5	–3.2	–0.16
Bio -fuels	5	–100	–5
Wind on shore	5	–0.4	–0.02
Wind off shore	5	0	0
CC- OTEC	5	0	0
Hybrid OTEC	5	0	0
Coal plant	5	–1	–0.05

Table 7. Sustainability percent on food growth index for the energy systems.

Energy systems/ Sustainability	Sustainability% allotted for food growth index	Sustainability% of the energy systems	Sustainability % on food growth index share
PV solar	12	25	3
Bio -fuels	12	0	0
Wind on shore	12	15	1.8
Wind off shore	12	15	1.8
CC-OTEC	12	90	10.8
Hybrid OTEC	12	90	10.8
Coal plant	12	0	0

would produce 2 million liters of potable water/day as the by-product availed free, which obviously would cater to the need of 1 million people. Thus hybrid OTEC can be assigned sustainability of 80% on this index.

Based on the above discussions, sustainability percent on potable water availability has been shown below in Table 8.

3.8 Economy Evaluation

In order to determine the sustainability percentage on economy evaluation aspect of an energy system, it would be needed to develop a scale of attaining 100% sustainability, whose electricity generation cost (LCOE/kWh) would be the cheapest one. Such value of least LCOE can never be less than \$0.02/kWh.

Thus we get an equation as below, for determining sustainability percent of an energy system.

Economic sustainability percent = \$0.02/kWh×100)/\$LCOE/kWh

where, \$LCOE/kWh=levelised cost of electricity/kWh of the concerned energy device.

Solar PV: At Jaipur, India, it could be observed from a study of solar PV power plant of 2.5 MW capacity using SANYO HIT-215NHE5 (Hetero-junction with Intrinsic Thin layer) PVmodule having P_{max} (maximum power) of 315 watts, and operating with a capacity factor of around 35%, that LCOE /kWh at 8% discount rate with 25 years life excluding the land cost was INR 10/kWh [33] which would be = \$0.13/kWh (considering conversion rate of INR to USD).

Thus sustainability % of solar PV on economy index = 0.02*100/0.13 = 15.4%.

Bio-Fuels: Biomass feedstock should be so chosen which would not be at the cost of agricultural produce, as far as practicable; and average LCOE for bio-mass is reported to be around \$0.045/kWh [34].

Thus sustainability % of bio-fuels on this index = 0.02*100/0.045 = 44.4%.

Wind energy: Wind energy -including on -shore and off-shore schemes -got their power cost appreciably lowered from technology advancement and increased volume of use in last few decades (wherever adequate resource potential of cut -in wind speed were available), and is becoming economically acceptable, nearing the cost of fossil fuel based power plants. Such power generation cost,

Table 8. Sustainability percent on potable water availability index for the energy systems.

Energy systems/ Sustainability	Sustainability% allotted on potable water availability index	Sustainability% of the energy systems	Sustainability % on potable water availability index share
PV solar	10	0	0
Bio-fuels	10	0	0
Wind on shore	10	0	0
Wind off shore	10	0	0
CC- OTEC	10	0	0
Hybrid OTEC	10	80	8
Coal plant	10	0	0

expressed as LCOE/kWh, has been reported to be \$0.042 and \$0.035, for on-shore and off-shore wind farms respectively [35,36]. The lower value of the later is mainly because of its availability of higher resource potential.

Thus, sustainability % of on-shore wind = 0.02*100/0.042 =47.6%.

For off-shore wind farms sustainability % = 0.02*0.035 = 57.1%

OTEC schemes (5MW net power): Capitalcost of such OTEC plant is considered to be \$300* 10^6 with spin of industries \$72*10^6 from available by products [37].

Capital recovery factor (CRF) considering 8% discount rate with 30 years life would be

$$8(1+0.08)^{30} / [(1+0.08)^{30} - 1] =0.08827433$$

Considering 95% capacity factor, annual electricity production with 95% capacity factor:

$$5*95*365*24*1000= 41,610,000 \text{ kWh}$$

Considering O&M to be 1% of leveled capital cost & taking into account the economic benefits derived from spin off industries, LCOE/kWh for OTEC plant = (Capital cost *CRF+ Levelised O&M cost - Spin off industries benefits derived)/(annual power generated in kWh) = \$0.49/kWh.

Thus, sustainability % of this OTEC plant = 0.02*100/0.49= 4.1%.

H-OTEC scheme (5 MW net power): H-OTEC scheme has an added advantage of producing potable water of 2 million liter water /day for 1 MW OTEC plant. Annual potable water production as by product from the same 5 MW OTEC =5*2*10^6 *365/1000 m^3 = 3,650,000 m^3 of potable water= 3650,000 m^3/41,610,000 kWh = 0.088 m^3/kWh potable water.

Since \$0.42/m^3 is required for producing potable water by desalination using MSF (multi-stage flash purification method of desalination of water [31], it can be considered lowering of LCOE by the same amount for H-OTEC.

Thus LCOE/kWh for H-OTEC = \$(0.49- 0.088*0.42)= \$ 0.45.

Thus, sustainability % of this OTEC plant = 0.02*100/0.45= 4.4%.

Coal based plants: It was reported that LCOE for a typical coal based power plant =\$0.28/kWh.

Thus, sustainability % of coal based powered plant = 0.02*100/0.028= 71.4%.

Based on the above discussions sustainability percent on economy evaluation has been shown below in Table 9.

3.9 Quality Improvement of Life

It would depend on the advancement of economic prospect of the society and other social parameters like, employment generation, food availability, scope on spread of education etc. In order to make quantitative assessment on sustainability in the perspective of energy systems, it would be quite logical to consider only the following three factors, which are:

a) commercial acceptability of the energy system concerned, which is the same as its economic viability.
b) getting easy access to the energy system concerned, which is the same as resource potential.
c) other social factors like, scope of employment generation, food availability etc.

Amongst the above three parameters, depending on relative importance, parameter ‘a’, the economic viability may be assigned 40% share of its total sustainability with the other two ‘b’, and ‘c’ items with 30% share for each.

Sustainability percent of this index on quality improvement of life, for different energy systems, have been estimated based on the above stated premise of sustainability distribution pattern.

Solar PV: Its (a) economy evaluation shows a value of 15.4% and (b) resource potential (for scope of installation in inaccessible areas) to be 70%. Factor “c” having moderate scope on employment generation to some extent and having scope of implantation in inaccessible areas, it can be said to be around 50%.

Thus total sustainability on this index = 15.4% of 40 (as

Table 9. Sustainability percent on economy evaluation index for the energy systems.

Energy systems/ Sustainability	Sustainability% allotted on economy evaluation index	Sustainability% of the energy systems	Sustainability % on economy evaluation index share
PV solar	16	15.4	2.5
Bio-fuels	16	44.4	7.1
Wind on shore	16	47.6	7.6
Wind off shore	16	57.1	9.1
5 MW OTEC	16	4.1	0.7
Hybrid OTEC	16	4.4	0.7
Coal plant	16	71.4	11.4

per Table 9) +70% of 30 (as per Table 2) and 50% of 30 = 42.2%.

Bio-Fuels: Its economy evaluation shows a value of 44.4% (Table 9) and resource potential to be 50% (Table 2) and in item c) it has an unique advantage on scope of use not only as transport fuel but also of energy production from waste materials and thus may be assigned a value of 70%.

Thus the total sustainability on this index = 44.4% of 40+ 50% of 30 +70% of 30= 53.8%.

Wind on-shore: Its economy evaluation shows a value of 47.6% (Table 9) and resource potential to be 30% (Table 2) and in item c)have less scope of employment generation, which is rather marginal, around 20% only.

Thus the total sustainability on this index = 47.6% of 40+ 30% of 30 +20% of 30= 34.0%.

Wind off-shore: Its economy evaluation shows a value of 57.1% (Table 9) and resource potential to be 50% (Table 2) and in item c) have less scope of employment generation, which is rather marginal, around 20% only.

Thus the total sustainability on this index = 57.1% of 40+ 50% of 30 +20% of 30= 43.8%.

OTEC schemes (5MW net power): Its economy evaluation shows a value of 4.1% (Table 9) and resource potential to be 90% (Table 2) and in item c) have huge scope of employment generation from enhanced marine species growth (fish, sea-weeds, abalone, mineral rich treated bottom layer ocean water) and opening up scope of spin-off industries and could be considered to attain a value of 80%.

Thus the total sustainability on this index = 4.1% of 40+ 90% of 30 +80% of 30= 52.6%.

H-OTEC (5MWS Net Power): Its economy evaluation shows a value of 4.4% (Table 9) and resource potential to be 90% (Table 2) and in item c) have huge scope of employment generation from enhanced marine species growth and opening up scope of spin-off industries and as well as scope of huge quantity potable water availed free, thereby with further improvement sustainability assessment, may be around 90%.

Thus the total sustainability on this index = 4.4% of 40+ 90% of 30 +85% of 30= 54.3%.

Coal plant: Its economy evaluation shows a value of 71.4% (Table 9) and resource potential to be 12% (Table 2) and in item c) have huge scope of employment generation from power plant as well as from coal mines which is labour intensive industry; though its harmful effect on human health and facilitating global warming is an impediment in improvement on quality of life. Thus by and large its overall scoring on societal index of item c), may be taken to be not less than 70%.

Thus the total sustainability on this index = 71.4% of 40+ 12% of 30 +70% of 30= 53.2%.

Based on the above discussions sustainability percent of the index on improvement in quality of life, has been shown below in Table 10.

Total sustainability: Combined effect on sustainability of the above stated 9 sustainability indices as may be effective from each of these 7 energy systems, are shown below in Table 11.

3.10 Discussions on the Results of Sustainability of the Energy Systems

A comparative study have been made on the total sustainability achievable (all the indices combined) of the different energy systems, inclusive of commonly used RE schemes, as per data derived in Table 11, as well their scope on improving upon the quality of life with prospect of economic growth, as could be derived from Table 9 (2nd column). This has been shown below in Figure 2.

Table 10. Sustainability percent on improvement in quality of life index for the energy systems.

Energy systems/ Sustainability	Sustainability% allotted on improvement in quality of life index	Sustainability% of the energy systems	Sustainability % on improvement in quality of life index share
PV solar	16	42.2	6.8
Bio-fuels	16	53.8	8.6
Wind on shore	16	34.0	5.4
Wind off shore	16	43.8	7.0
5 MW OTEC	16	52.6	8.4
Hybrid OTEC	16	54.1	8.7
Coal plant	16	53.2	8.5

Table 11. Total Sustainability percent of different RE schemes inclusive of a coal-based plant.

Energy Scheme/ indices	PV solar	Bio-fuels	Wind On shore	Wind off shore	5 MW OTEC	Hybrid OTEC	Coal plant	Data source
Resource	7	5	3	5	9	9	1.2	Table 2
GHG saving	14.5	14.0	14.8	14.7	15	15	0	Table 3
Flora & Fauna	0	4.8	–1.6	–0.8	5.6	5.6	–4.0	Table 4
Human health	–1.2	2	0	0	7.2	7.2	–5.6	Table 5
Land loss	–0.16	–5	–0.02	0	0	0	–0.05	Table 6
Food	3.0	0	1.8	1.8	10.8	10.8	0	Table 7
Water	0	0	0	0	0	8	0	Table 8
Economy	2.5	7.1	7.6	9.1	0.7	0.7	11.4	Table 9
Life quality	6.8	8.6	5.4	7.0	8.4	8.7	8.5	Table 10
Grand total	32.44	36.5	30.98	36.8	56.7	65.0	11.45	

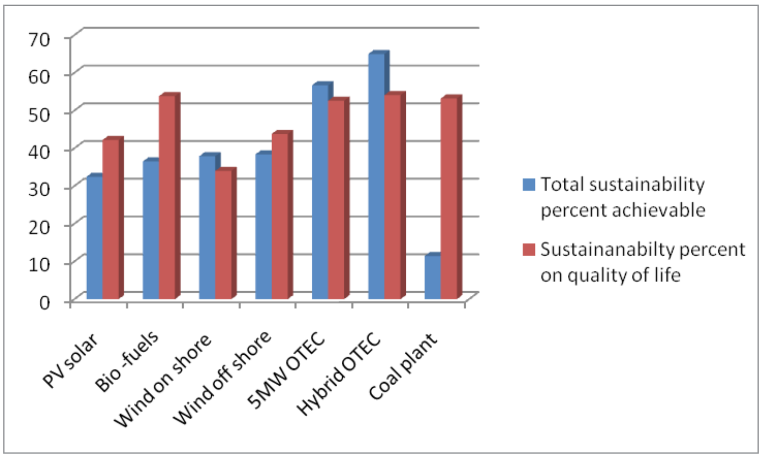

Figure 2. Total sustainability versus quality improvement of life for competing energy systems.

It could be observed that total sustainability of RE schemes shows highest value for hybrid OTEC followed by 5 MW CC-OTEC, wind (both off-shore and on-shore ones) bio-fuels and PV solar, respectively.

It was also noted from closer introspect on Figure 2, that coal plant having minimum total sustainability of less than 12% - affecting global warming, resource depletion and affecting human health, does have more than 50% sustainability on the criterion on quality improvement of life only for its commercial acceptability, unlike other RE systems with rather less commercial acceptance, though wind energy's economic viability is only a little above coal plants. But OTEC schemes, despite its low values on economic viability, competes with coal, rather better when considered its hybrid schemes, over the criterion of 'improving upon the quality of life'. Bio-fuels also shows high sustainability on this criterion like OTEC, followed by off-shore wind, PV solar & onshore wind respectively.

Thus, OTEC opens up huge scope of economic growth around its application site, with its inherent huge scope of facilitating food security, employment generation, water security besides energy security.

It is hence been considered pertinent to examine scope of cost reduction of OTEC system, so that it can emerge as a commercially viable technology as well.

4. Scope of Electricity Generation Cost Reduction of OTEC Schemes

The only limitation of OTEC is its, high capital cost involvement for installation and also poor power conversion efficiency. The following four-fold approaches are being suggested to address these problems. They are:

1) Economic assessment of OTEC from power generation cost aspect (LCOE).
2) Using heating of solar irradiation for increasing power conversion efficiency, modified as SOTEC.
3) Storing electricity generated from production of hydrogen and thus saving long cable cost and transmission loss.
4) Hybridization of OTEC schemes.

4.1 Economic Assessment of OTEC

The capital cost of OTEC varies asymptotically making its LCOE/kWh to vary according to the size of OTEC plant, as shown below in Figure 3 [40]. It would be obvious from Figure 3, that the break-even point of electricity generation cost of OTEC is around 40 MW, below which it shoots up rather sharply.

Thus OTEC scheme of 40 MW should be the minimum size for commercial type OTEC plants, where 100 MW OTEC plant shows minimum power generation cost.

4.2 Increasing Power Conversion Efficiency Using SOTEC

The power conversion efficiency in OTEC scheme is around 3-5% only, which is caused from low temperature difference (20-30) K between SOW & DOW. This makes electricity generation cost of OTEC rather high. Saga University (Japan) researchers proposed an improved OTEC scheme that would not only utilize ocean's thermal energy for its electricity production, but also solar thermal energy as the heat sources effecting further heating of the SOW and/or heating up the working fluid NH_3, and thereby increase its power conversion efficiency. This modified OTEC was termed SOTEC [41].

They proposed using low cost flat plat type solar collector for making an additional temperature rise utilizing heating effect of the sun's radiation, and thereby further warming up the SOW, termed SOTEC-1, which could also heat up the working fluid (NH_3) exiting the evaporator termed as SOTEC 2. The solar collector could thus elevate the temperature of turbine inlet fluid to an additional 20 K (>40 °C) and thereby increasing the Rankine cycle efficiency from 3.4 to 7.6 [41]. Schematic diagram of these two types of SOTEC are shown below in Figure 4.

It may be added that normally only 0.5% of water of

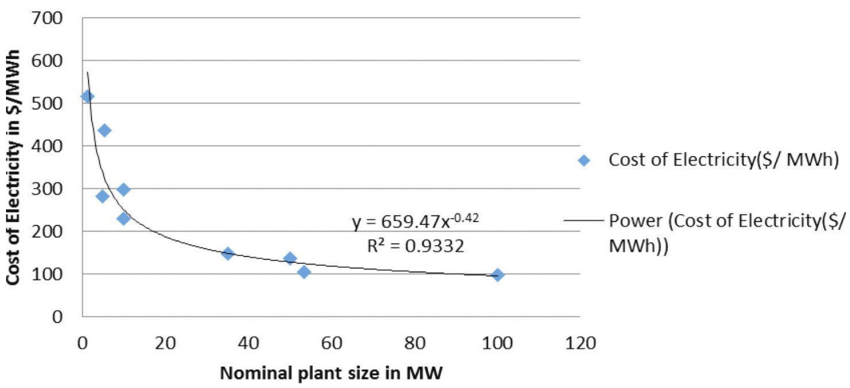

Figure 3. Cost of electricity versus OC-OTEC plant site Copyright© 2016 by Taylor & Francis

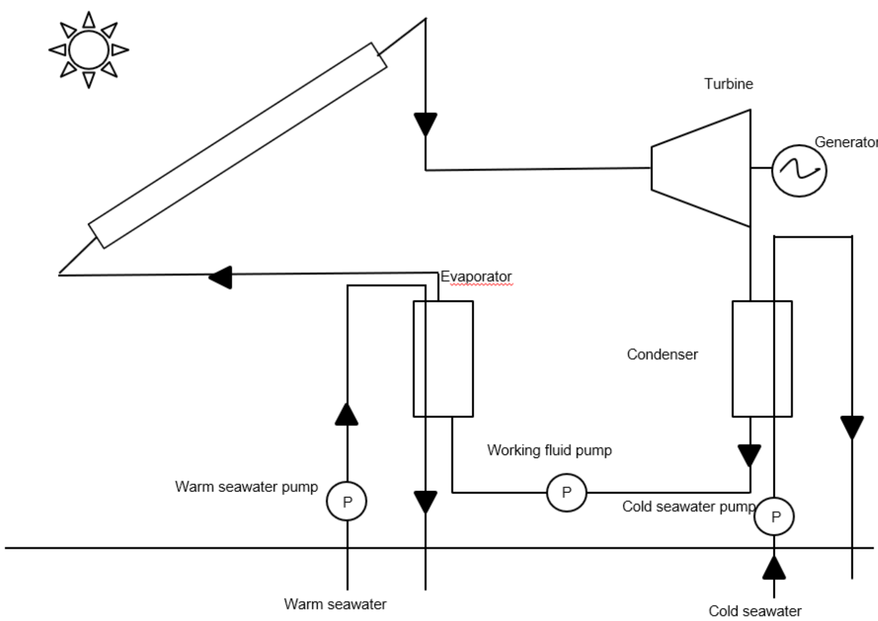

Figure 4. SOTEC-1. Schematic diagram giving the components [41].

the SOW feed gets evaporated in OC-OTEC or hybrid OTEC, since the high latent heat of water evaporation effecting cooling, stops further evaporation (Steam generation rate from SOW = Heat absorbed from SOW/latent heat of evaporation at that temperature and pressure of the vacuum chamber pressure of 0.03 bar). But with higher temperature feed of SOW is bound to make more water evaporation with additional potable water availability as well, besides increasing power conversion efficiency of SOTEC.

4.3 Hydrogen Generation from OTEC

The electricity generated from OTEC may be utilized by storing it through hydrogen production by electrolysis and thereafter converting the stored hydrogen to electricity through fuel cell route. On the other side storage of hydrogen is made converting it to hydrogen enriched product like CH_3OH, NH_3, $NaBH_4$, etc. - where hydrogen availability from hydrolysis in fuel cell could be more than the amount stored.

In order to achieve better performance of electrolysis proton exchange membrane electrolyser (PEME) has been suggested to be used [42]. It may be added that along with hydrogen there is simultaneous production of oxygen, which would be 8 times the weight of hydrogen produced.

Such storage of hydrogen utilizing OTEC generated power would not only save cost of cable line layout but would also address power transmission loss in cable line connection reaching the grid line. In fact, it has been opined that advanced 2nd/3rd generation OTEC with its huge benefits of by-products is likely to lower electricity production so cheap, that OTEC would be considered a good option opening up the scope of use of hydrogen as the future energy source [43].

4.4 Hybridization of OTEC

Hybridization of OTEC may be made by combining both the closed cycle OTEC (CC-OTEC) and open cycle OTEC (OC-OTEC) combined together, as shown in the flow-sheet diagram in Figure 5, given below. The left side showing OC-OTEC cycle would be mainly for water production, while the left one shows CC-OTEC cycle for power generation [44]. Pilot plant project of the same is going to be set up for further study by UTM research team at Malaysia.

It may be added that such hybridization may also be made combining PV solar as well as off-shore wind schemes utilizing the huge platform of large scale OTEC plant ship as well as in platforms of the spin off industries which may come up from hydrogen generation industries. The PV scheme thus installed on OTEC plant ship would save land requirement cost of PV cells. Application off-shore wind schemes over OTEC ship would lower its power generation cost by eliminating its costly foundation cost in the ocean bed, in addition to its scope of higher resource potential from availability of higher wind speed far off from shore.

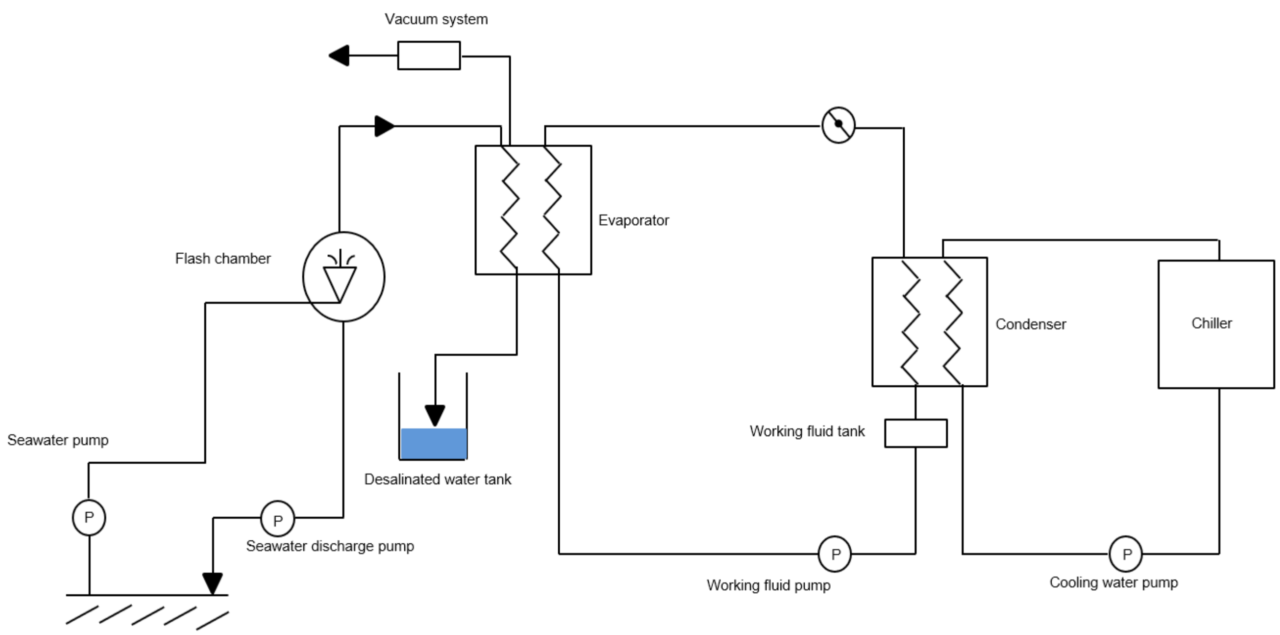

Figure 5. Basic cycle of Hybrid OTEC scheme [44].

5. Conclusions

It could be observed from the sustainability assessment study that scope of saving GHG emission for averting global warming though more than 95% from most of the RE schemes studied, but for OTEC schemes it is the best and reaches 100% mainly from sequestering of CO_2, which is an added advantage of OTEC.

As regards the potential of economic growth, ascertained from the sustainability index on quality improvement of life, OTEC can be considered equivalent to coal power plants, rather better in case of hybrid schemes, despite the inherent limitation of its higher cost of power generation with coal having the advantage of commercial; acceptability with lowest power production cost.

Coal plants are however fully unsustainable energy scheme with sustainability less than 12%. Bio-fuels and OTEC only competes with coal as regards scope on quality improvement of life is concerned with solar and offshore wind coming next in the rank, the former having the scope of application in inaccessible areas while the power generation cost of the latter is nearly at par with coal plant.

OTEC however has huge potential on the scope of cost reduction in power generation from its application of higher capacity plants (minimum 40 MW), increased power conversion rate using SOTEC and diverting its power generation to hydrogen production and thus storing electricity.

Besides energy security OTEC schemes, particularly Hybrid OTEC, provide water security food security and a host of spin-off industries.

Conflict of Interest

There is no conflict of interest.

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Non-Metallic Material Science
https://ojs.bilpublishing.com/index.php/nmms

ARTICLE

Activated Carbon Precursors Derived from Jute Fiber: Social, Economic and Environmental Development

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ARTICLE INFO

Article history
Received: 18 October 2022
Revised: 1 November 2022
Accepted: 9 November 2022
Published Online: 15 November 2022

Keywords:
Carbon fiber
Biodegradability
Precursors
Derivation

ABSTRACT

Activated carbon fiber (ACF) is undoubtedly one of the most significant carbon nanocomposite materials to consider from the perspective of application in adsorption. Compared to other commercial porous storage materials, it offers many benefits. With a fiber-like shape and a clearly defined porosity structure, activated carbon fiber (ACF) is a potential microporous material. In general, synthetic carbon fiber (CF) can be used to commercially make ACF with the inclusion of an activation procedure. High packing density, outstanding volumetric capacity, rapid adsorption/desorption, and ease of handling are some of the unique properties of ACF. The production expenses of ACF are made up of fiber processing costs and activation costs, both of which are comparatively more expensive than those of other activated carbons. Recently, researchers have indicated that the manufacturing of ACF from less expensive precursors might be accomplished by preparing activated carbon (AC) from agricultural wastes. In comparison to synthetic ACF, there were fewer details and publicly accessible sources of information about these natural fiber derived ACF. The cost of processing fiber is higher and shaping fiber into the correct shape is challenging. In this study, social and environmental compliance, economic development, advantages of carbon fiber,and applications of carbon fiber are discussed.

1. Introduction

ACFs (activated carbon fibers) are porous carbon fibers having a fiber form and a well-defined porous structure that can be manufactured with a high adsorption capacity [1]. Activated carbons (ACs), which are carbon-based structures, are versatile and effective materials that have been widely used in a variety of applications, including catalysts and catalyst supports, adsorbents in chemical recovery operations, industrial purification, air purification, removal of organic and inorganic pollutants from water, anti-corrosion coatings, and enhanced oil recovery [2]. Carbonaceous materials are in high demand around the world

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DOI: https://doi.org/10.30564/nmms.v4i2.5157

due to their unique features and wide range of applications. However, the high cost of commercial carbonaceous materials prevents them from being used on a broad basis. As a result, novel precursors for producing carbonaceous materials that are less expensive and more efficient must be investigated. As a result, researchers from all over the world are interested in carbonaceous materials made from renewable and low-cost agricultural resources, such as agricultural byproducts and waste as precursors, that contain enough carbon in their structure [3]. Activated carbon fibers have a large specific surface area, superior adsorption performance, and electrical conductivity, which distinguishes them from other porous carbon materials. Activated carbon fiber has the following benefits: (1) The activated carbon fibers' micropores are directly exposed to the fibers' surface, allowing for molecular and ion adsorption and desorption. (2) Activated carbon fiber (ACF) electrode materials can be developed without a binder during the assembly process, lowering internal resistance. (3) Because they have a lower density than activated carbon powder, they can produce higher gravimetric specific capacitance. (4) ACF possesses adaptable properties that can be used to create adaptable devices [4]. Biomass-based products made from natural resources have recently gotten a lot of interest in academia and industry. This is owing to benefits such as sustainability, recyclability, cost-effectiveness, and environmental friendliness [5]. Although the fibers are not discontinuous, limited in fiber length, and have relatively low mechanical properties in comparison to conventional rayon-based and PAN-based carbon fibers, it would be desirable and useful if carbon fibers or activated carbon fibers could be made from biomass-based natural fibers, which are abundant in nature and less expansive [6]. Jute fiber, on the other hand, is a natural fiber made from jute plants. Jute is commonly referred to as the "golden fiber" and is sold under two names: white jute (Corchorus capsularis) and tossa jute (Corchorus olitorius) [7]. Jute fiber (Corchorus capsularis) is commonly used because it is one of the most affordable cellulose-based natural fibers and has a high Young's modulus compared to many other natural fibers. It also contains a significant amount of cellulose and lignin. The chemical composition of jute fiber includes cellulose (64.4%), hemicellulose (12%), pectin (0.2%), lignin (11.8%), water soluble (1.1%), wax (0.5%), and water (10%), cellulose (64.4 percent) [8]. Jute fiber is made up of many cells. These cells are made up of cellulose-based crystalline microfibrils that are joined to a full layer by amorphous lignin and hemicellulose. A multiple-layered composite is formed when numerous cellulose and lignin/hemicellulose layers in one primary and three secondary cell walls bind together. The composition (ratio of cellulose to lignin/hemicellulose) and orientation of the cellulose microfibrils differ in these cell walls. Carbonization of natural fibers can result in significant weight loss and thermal shrinkage. The physical, chemical, and morphological properties of cellulose-based carbon fibers are influenced by the chemical pre-treatment as well as the heat-treatment condition. Jute fiber is one of the most widely available, longest, and strongest natural fibers, as well as a low-cost (0.5 USD/kg) lignocellulosic fiber. Jute is the second most significant fiber in the world. Jute fiber is the most widely used natural fiber on the planet. Its popularity has grown dramatically as a result of its unusual combination of physical, chemical, and structural qualities, as well as mounting environmental concerns [9]. Jute fibers provide high thermal and acoustic insulating characteristics, with mild moisture resorption and no skin irritations. Jute fiber is currently produced at 3.2 million tons per year around the world and is utilized in a variety of applications. The bag cloth industry consumes most of the jute fibers available on the market. Jute bags have gained popularity as an environmentally beneficial alternative to both nonbiodegradable poly bags derived from petroleum and paper bags that use a lot of wood. Every year, a large volume of jute fibers is wasted and dumped in landfills, either as slivers from jute cloth manufacture or as old clothes following the end-of-life of the product [10]. As a result, jute is regarded as a low-cost, widely available, renewable, and environmentally benign carbon source. As a result, a lot of work is being done to figure out how to convert jute stick and fiber as precursors into various sorts of innovative carbon compounds using diverse methods [11]. Water treatment, electrochemical energy storage, hydrogen storage, and electrochemical sensors are just a few of the possibilities for jute-derived carbon. However, no study has yet focused on summarizing the various procedures used to manufacture carbon from jute, as well as the usage of the carbon obtained for various applications. As a result, we've compiled the study on the preparation and application of activated carbon produced from jute in this review. Figure 1 indicates activated carbon fiber composites.

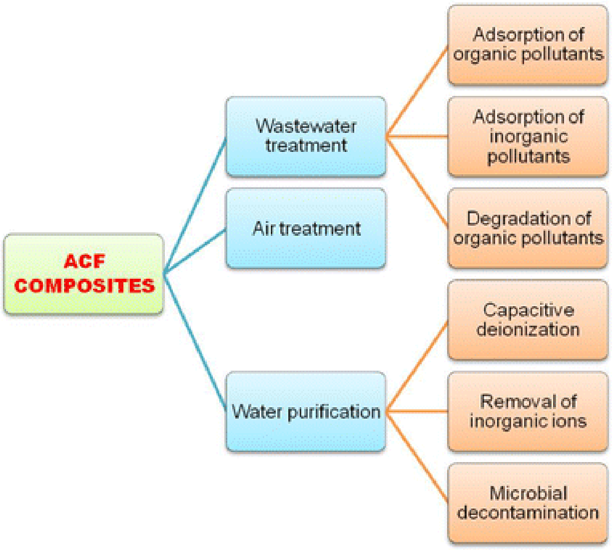

Figure 1. Activated carbon fiber composites [12]

2. Objectives

The objective of this research is to investigate at the advanced possibilities and implications of using jute to form activated carbon. It is also designed to look for innovative jute applications and their prospects. The use of accessible natural resources and the quest for cost-effective options for activated carbon extraction are the objectives of this research. The focus of this research was to analyse the jute fibre as well as to create and characterize the activated carbon that resulted.

3. Social and Environmental Compliances

Jute is good for both people and the environment. It contributes to environmental cleanliness by using fewer fertilizers. It has numerous advantages, but its significance has not yet been fully appreciated. Jute provides underprivileged people with work options. Jute is a time-consuming crop to grow. Every 0.4 hectare (1 acre), the labor cost of raw jute cultivation is roughly 60-70 percent of the total cost. Dried jute leaves and plants are edible and supply disadvantaged people with free or low-cost meals. Jute is gathered in flooded fields where fish can develop, and these fish provide a good source of nutrition. Jute stalks, which are obtained by remining jute plants after the fibres have been removed, are used as cooking fuel and building materials, contributing to deforestation. The widespread usage of already-banned plastic bags has harmed Jute's popularity. The cost of production is the primary reason for polythene's increased popularity. Jute is a little more expensive than cotton. Polythene, on the other hand, is harmful to the environment because it is not biodegradable [13]. Polythene production releases a large amount of carbon dioxide into the atmosphere, which contributes to global warming. It's also bad for the soil because it depletes the soil's fertility. In terms of environmental benefits, it points out that jute takes CO_2 from the environment as it grows and returns it when it decays. The researchers found that throughout the jute growing season, one hectare of jute plants consumes 15 tons of CO_2 and releases 11 tons of oxygen. In comparison to carbon dioxide produced during polypropylene manufacturing, carbon dioxide emissions from transporting and milling jute fibres are one-sixth. CO_2 in the atmosphere is a significant greenhouse gas that contributes to global warming. As a result, jute can play an important role in environmental protection while also lowering CO_2 levels in the atmosphere. Synthetic goods obstruct water movement, resulting in flooding and water logging. It also produces a large amount of non-biodegradable waste, which is a major issue. Because of its physical and chemical qualities, such as strong tensile strength, low extensibility, and superior breathability, jute has a wide range of applications [14]. It also has significant environmental benefits. Figure 2 indicates the flow diagram showing the steps in the production of Activated carbon.

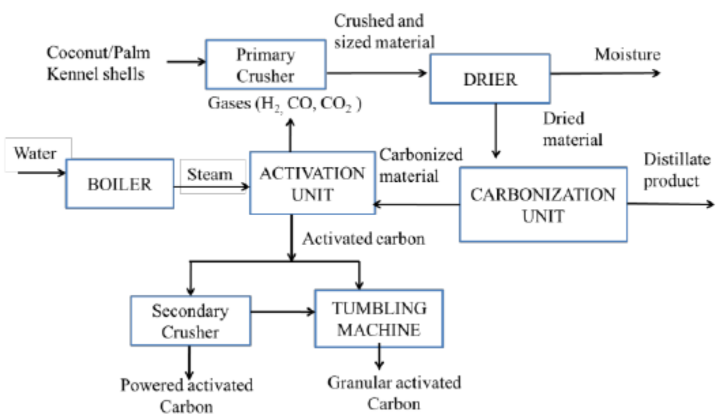

Figure 2. Flow diagram showing the steps in the production of Activated carbon [15]

3.1 Biodegradability

The most essential characteristic of jute is that it is biodegradable and non-polluting. It produces no trash and helps to keep the environment clean.

3.2 Cleaning the Environment

According to studies and research, throughout a season of around 100 days, one hectare of jute plant may absorb up to 15 tons of carbon dioxide and release 11 tons of oxygen. This is great news for the environment, which is already poisoned.

3.3 Contributes to Decreasing Environmental Pollution

Jute goods aid in the reduction of environmental pollution by reducing the demand for non-biodegradable plastic bags that contaminate the environment. Jute bags are more handy than plastic bags since they may be reused multiple times.

3.4 Eases the Pressure on Natural Oil Stock

Petrol is a renewable natural resource with a finite supply. Petroleum products are used to make plastic and poly bags. This places a lot of strain on our finite petroleum supply. As a result, jute might help to lighten the load.

3.5 Requires Less Land for Cultivation

It necessitates less land to cultivate. When compared to other goods, jute requires less land. This could be beneficial in the production of other crops, such as food crops. This will assist in the reduction of food demand.

3.6 Less Requirement of Fertilizers & Pesticides

When compared to a crop like cotton, jute uses fewer fertilizers and insecticides. As a result, the environment will be cleaner since soil pressure will be reduced. The leftovers from the jute crop, including as leaves and roots, contribute to improve soil condition and fertility.

3.7 Improves the Soil

Jute improves the condition of the soil while also increasing its fertility.

3.8 Environment Friendly Practices

Jute and its by-products are produced using environmentally friendly methods that have a minimal impact on our environment.

3.9 Helps in Maintaining Eco Balance

In our environment, trees play a critical function. By promoting jute and its products, we can maintain a perfect eco-balance. This will aid in the growth of trees, which will aid in the resolution of issues such as loss of fertile soil, rain shortages, and reduced forest cover.

4. Economic Development

The jute plant is a cousin of the hemp plant. Jute, on the other hand, is free of narcotic components and odor. Jute can be mixed and matched with both synthetic and natural fibers [16]. Jute may absorb a wide range of cellulosic dyes, including natural, vat, sulfur, pigment, and reactive dyes. The need for blended jute and cotton fibre will rise day by day as the desire for natural comfort fibres rises. Fabrics made of jute and cotton yarns can help save money on wet processing processes. Jute and wool can be mixed. For blending with wool, caustic soda is used to improve the pliability, softness, and appearance. To add the characteristics of flame resistance in jute, liquid ammonia is used to treat with flame proofing agents. Along blending with wool, new concept, technology, and techniques are attempted to blend jute with polyester and acrylic for manufacturing diversified yarns. These diversified jute blended yarns are used to produce value added products such as home textiles, decorative fabrics, geo-textiles, carpet backing cloth and so on. These end fabrics from diversified jute blended yarns poses different qualities, comfort, and cost benefits. Bangladesh currently earns roughly $600 every ton of raw jute exported. Exporting these value-added diverse jute products can boost the export value by tenfold. Bangladesh can earn $3,000-$10,000 by exporting one ton of these various items, depending on quality and kind. He expressed optimism about increased jute usage, stating that the obligatory packaging act for utilizing jute bags contributed to a rise in manufacturing of more than 1 billion jute sacks. Local enterprises increased the export base of jute items from 135 in 2016-2017 to 240 in 2017-2018. By 2021, the market for jute bags is expected to reach $2.6 billion, while the market for home textiles including garments and fabrics will reach $130 billion. Jute has the potential and prospect of being the next important driver in the economy with value addition and new applications, whereas garments are currently the main key driver in Bangladesh. The country requires a new growth motor, which jute and jute products may provide. However, emphasize the importance of collaboration between the jute and textile industries. In Bangladesh, around 0.5 million people are directly employed in the jute industry.

However, there is a scarcity of skilled workers. Bangladesh is currently undergoing the fourth Industrial Revolution [7]. As a result, the fourth Industrial Revolution's technology should be applied to the development of the jute industry. As a result, market analysis, international branding of jute products, implementation of investment-friendly policies, worker skill development, and the establishment of specialist jute mills are all key variables to consider while exploring jute's economic potential.

5. Advantages of Activated Carbon Fiber

Activated carbon fibers are promising solid materials that, when compared to granular activated carbon and powdered activated carbon (PAC), offer remarkable characteristics (GAC). Numerous researchers have expressed interest in continuing their research on ACF [17]. The followings are the primary traits and benefits of ACFs: Exceptionally high adsorption capacity and surface area: According to T.J. Mays, ACF has high adsorption capabilities because it lacks minimum mesopore gaps and non-adsorbing macropores [18]. For instance, T.-H. Ko and colleagues thoroughly investigated and found that new tiny pores were created in fibers because of etching of the ACF surface during the activation process. These pores, which were between 10 nm and 30 nm in size, vanished throughout the activation phase. After the activation procedure, the surface area increased by several hundred times. Activation can encourage the growth of new pores as well as the expansion of existing pores. Compared to unactivated carbon fiber, these ACF show a greater porous structure and capacity for basic dye adsorption [19]. While in GAC, the adsorbate gas molecules must first travel via macropores and mesopores before reaching micropores, in ACF, the majority of micropores are exposed to the fiber surface and the adsorbate gas directly [20]. According to Manocha (2003), in this instance, the rates of toluene adsorption and desorption on ACF are significantly higher than those on GAC. Of course, increasing the temperature on ACF can speed up this desorption of toluene gas more [21]. ACFs are a lightweight, highly flexible material. They can simply proceed with the product in various sorbent shapes and forms, such as woven clothing, non-woven mats, papers, and felts. These materials' flexibility also directly improves the handling and packing efficiency for specific specialized applications [22]. For instance, ACFs can be utilized as capacitors, deodorants in refrigerators, and filtration candles for minor purification systems. According to research by Tanahashi and colleagues, ACF electrodes may be tailored more precisely than GAC electrodes when used as capacitor electrodes [23]. ACF is combined with wood pulp utilizing paper-making technology to increase material toughness, and it is afterwards produced as polarizable electrodes for electric double layer capacitors. Using this method will prevent issues that have occurred during the packing of the grains or power- ders of conventional ACs [24]. Narrow and homogeneous distribution of pore sizes: The pore size of ACFs is primarily composed of micropores, which are smaller than the 2 nm limit set by IUPAC. Pore diameters typically vary from 0.8 nm to 1 nm (ultra-micropore area). Figure 3 indicates Activated carbon market global forecast.

Figure 3. Activated carbon market global forecast [20]

6. Application of Activated Carbon Fiber

Activated carbon is employed in a variety of industrial processes nowadays, such as gas and air cleaning with conventional reusable substance recovery methods. New applications have developed as a result of increased environmental consciousness and the implementation of tight emissions regulations, most notably in the field of air pollution removal. Additionally, the treatment of water, including drinking water, groundwater, service water, and wastewater, is using activated carbon more and more. Its main function in this situation is to adsorb dissolved organic impurities and to remove flavors, colors, and odor-causing agents from halogenated hydrocarbons and other organic contaminants.

6.1 Storage of Natural Gas

Due to its relative safety and lower pressure (3 MPa ~ 4 MPa) at room temperature for the application of methane adsorption, adsorbed natural gas (ANG) is a more preferred technology than compressed natural gas (CNG). Without reducing deliverable capacity, ANG may be able to achieve gas storage pressure with a single-stage compressor. In ANG technology, natural gas is frequently stored in a thin cylinder that is packed with very porous adsorbents [25]. Numerous studies on methane storage have been conducted with an emphasis on the development and characterization of carbon-based porous materials that can achieve the best methane adsorption capabilities and delivery. According to the results of these studies, activated carbon fiber (ACF) is the best adsorbent for use in methane storage applications and has a significant advantage over AC [26]. Figure 4 indicates the activated carbon fiber for energy storage.

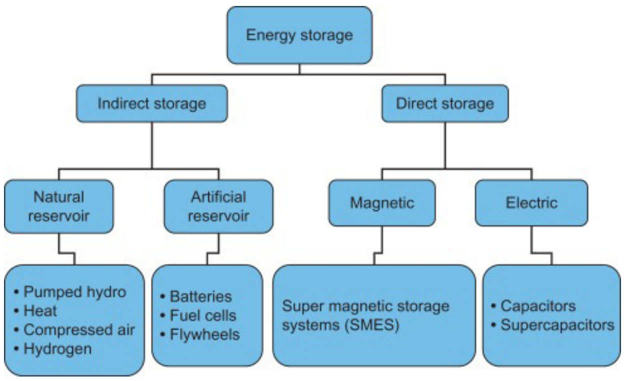

Figure 4. Activated carbon fiber for energy storage [27]

6.2 Removal of SO_2 and NOx

ACF's use in the removal of SO_2, and NOx has been widely documented elsewhere following AC as a primary material. The effectiveness of activated carbon fibers based on pitch for the removal of SO_2 and NOx has been examined by the team led by Mochida et al. The results showed that the maximum SO_2 reduction activity in the presence of water at 25 °C was obtained in pitch based ACF that had undergone heat treatment in nitrogen at temperatures ranging from 600 to 900 [28]. Through the combination of the TiO_2 photocatalyst and urea, reduction of air NOx to safe N_2 was successfully accomplished utilizing pitch based ACF. Utilizing natural wind, the ACF for NOx removal system in the atmosphere could function well in urban areas. The unusual porous nature of ACF, which allows the adsorption process to proceed more quickly, gives it an edge over traditional AC in gas-phase adsorption. In essence, the structures of ACFs consist of readily accessible microporosity for the adsorbate and a lack of diffusion within meso- and microporosity that limits transfer [29]. The most urgent issue currently facing fashion companies is sustainability, which should come as no surprise given that the sector is responsible for 10% of global CO_2 emissions (more than international aircraft and shipping combined) [30]. Figure 5 indicates Activated carbon fiber SO_2 and NOx removal process.

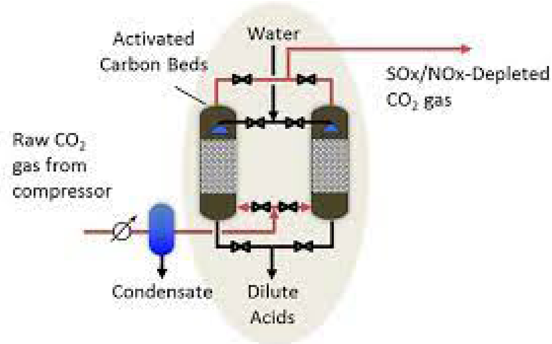

Figure 5. Activated carbon fiber SO_2 and NOx removal process [31]

6.3 Water Purification

One of the most vital elements on earth is water. To guarantee that the water supply is pure and fit for use, it must be purified, toxins from wastewater must be removed, and bacterial development must be inhibited. Granular activated carbon was formerly a widely used material for water filtration. Recent research, however, suggests that ACF may be a superior choice than GAC as a media for water purification [32]. ACF can perform superior adsorption capacities and rates for low molecular weight pollutants, and it may be inferred from those investigations. ACFs also have the added benefit of being simpler to regenerate. However, due to the fiber structure of ACF, bacteria are easily recognized and propagated. Water pollution and water quality issues may result from the presence of bacteria. Oya and his team created antibacterial activated carbon fiber with the inclusion of silver for water purification in 1993 to address this issue. Applications of these antibacterial ACF revealed antibacterial Escherichia coli and Staphylococcus aureus [29]. By combining natural materials, technology, and information into effective technologically, designers can produce new forms of eco-friendly materials without using dangerous chemical production methods [33]. Figure 6 indicates the activated carbon fiber water purification process.

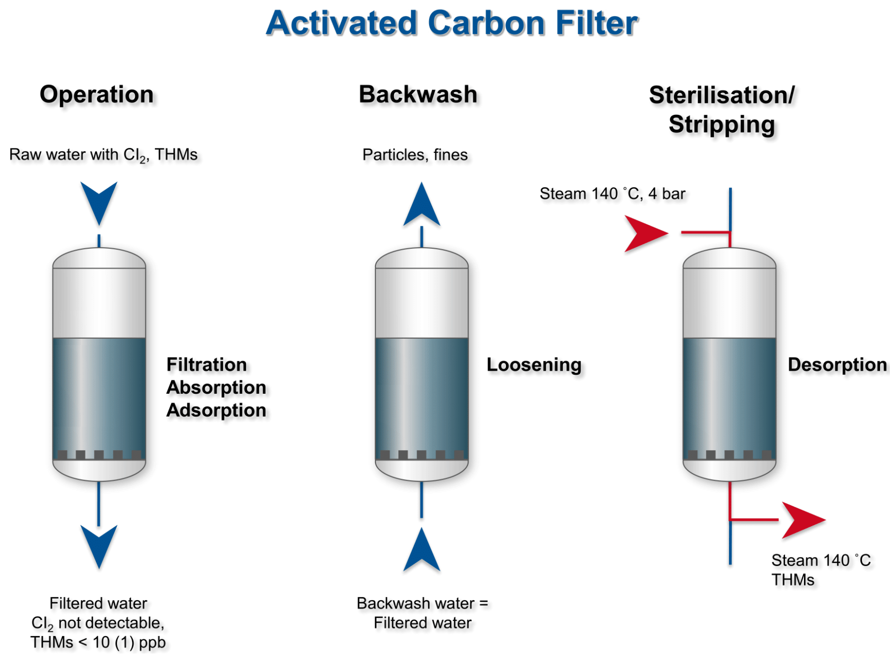

Figure 6. Activated carbon fiber water purification process [34]

7. Conclusions

According to the more typical powder or granular forms of porous carbon, ACFs provide several important advantages. High rates of adsorption from the gas or liquid phase are among them, as well as surfaces with high surface areas and adsorption capacities. As a result, activated carbon fiber combines the greatest attributes of both carbon fiber and activated carbon. The advantages of ACFs over conventional active carbon are their increased adsorption capacity, bigger surface areas, faster adsorption rates, and simplicity of production. ACFs can be created by synthesizing them from a variety of basic materials, including phenolic resins, mesophase pitch, pitch fiber, polyacrylonitrile, and biomass**.** The process used to activate carbon fibers has a significant impact on how porous they are. Increased pore production and continued pore size growth may be facilitated by activation added to the process. The process of activation can be carried out chemically or physically. The activated carbon fiber is cleaned during this procedure of the disordered carbons that obstruct the pores. Pore size distribution and porous structures in the manufacture could be customized through proper precursor carbon fiber selection, activation technique, and experimental circumstances. Materials for synthesizing activated carbon fibers (ACFs) for required applications. The raw material, activation procedure, pore structure, surface roughness, and surface functionalities are only a few of the variables that affect the adsorption capacity of ACFs.

Conflict of Interest

There is no conflict of interest.

Funding

This paper received no external funding.

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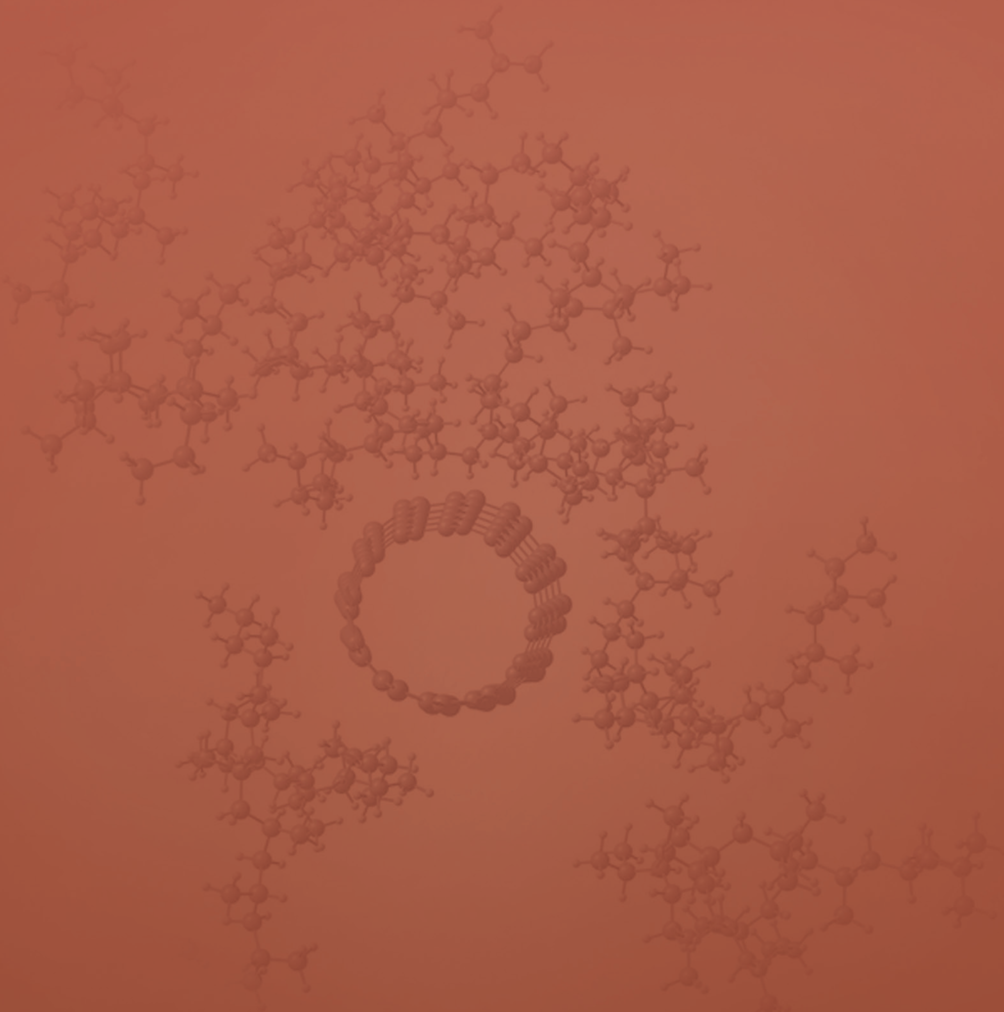

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