Journal of Manufacturing Processes 89 (2023) 124–131

Contents lists available at ScienceDirect

Journal of Manufacturing Processes

journal homepage: www.elsevier.com/locate/manpro

Life cycle assessment of carbon fiber and bio-fiber composites prepared via vacuum bagging technique

Karthikeyan Ramachandran *, Constance L. Gnanasagaran *, Ashish Vekariya

School of Engineering & the Enviornment, Kingston University, Roehampton Vale Campus, London SW15 3DW, United KIngdom.

ARTICLE INFO

Keywords:
Life cycle assessment
Carbon fiber composites
Biocomposites
Vacuum bagging technique
Global warming potential

ABSTRACT

Over the past few decades, increasing demand for light weight material have grown in various applications including aerospace, and other structural applications with added focus on green engineering and sustainability. Particularly in aerospace industries, utilisation of carbon fiber composites results in increased rate of pollution due to its inability to be repaired and recycled. Therefore, it is envisaged that migrating to biocomposites could be the solution forward depending on the manufacturing techniques. This life cycle assessment concentrates on understanding the emission rate of vacuum bagged carbon fiber and biocomposites with focus on its recycling abilities. In this study, carbon composites indicated a global warming potential (GWP) of 54 kgCO_2Eq. whereas biocomposites showcased 12 kgCO_2Eq. This implies that GWP of biocomposites were approximately four times less than carbon composites and if pesticides and fiber spinning are controlled, emission could be further reduced along with the overall energy consumption along with other emissions. Although biocomposites showcased lower environmental impact in mostly every scenario, the transition towards biocomposites still requires research to fulfil gaps with regards to the enhancement of mechanical properties compared to carbon fiber composites.

1. Introduction

The number of countries declaring pledges to achieve net-zero emissions has been constantly growing [1]. Despite efforts carried out by governments to tackle global warming, carbon dioxide (CO_2) emissions from energy production and industries have not declined but rather increased by 60 % since the United Nations Framework Convention on Climate Change in 1992 [2]. Albeit global commitments and actions till date, world still fall short of what is needed to limit the rise in global temperature to 1.5 °C and deter the adverse effects of climate change [2,3]. These environmental concerns lead researchers and industrials to develop alternatives to reduce the usage of petro-sourced materials [1,4–6].

In past few decades, transportation, manufacturing and construction industries have been the largest contributors to harmful gas emissions. Around 30 % of greenhouse gas emissions are from manufacturing processes in industries resulting in 44 % of CO_2 emissions which are contributed either directly or indirectly from the same source [7]. Therefore, it is vital to assess the emissions throughout the life cycle of a material and evaluate the impact on environment. In manufacturing and production industries, major emissions are contributed by choices made in supply chain and logistics (SCL), overall energy consumption and equipment utilised [8,9]. Environmental impacts from SCL particularly from transportation and structural elements like warehouses include toxic wastes, water pollution, loss of biodiversity and deforestation which causes long-term damage to ecosystems via hazardous air emissions and greenhouse gases (GHG) [10]. The amount of electricity used in the industries mainly for manufacturing, lighting, heating, ventilation and air-conditioning reflects on the amount of fossil fuels consumed to produce electric energy [11]. These fossil fuels emit air pollutants that are very harmful to the environment while burning by releasing CO_2 into the atmosphere along with other greenhouse gases [5,9]. Thus, replacement of energy generated from fossil fuels is of prime importance to meet Net Zero Emission target in the UK and to tackle other related issues like global warming [7,8].

Pathways to decarbonization are available and readily implementable for many sectors from a technical perspective including conversion from fossil fuels to renewable resources and use of more repairable, recyclable and biocompatible materials to manufacture transportation systems and structures [5]. However, to manufacture these renewable sources such as wind turbine blades and transportation systems like aircrafts, huge amounts of carbon fiber composites are utilised [11]. For

* Corresponding authors.
E-mail addresses: K1825123@kingston.ac.uk (K. Ramachandran), constance.g@kingston.ac.uk (C.L. Gnanasagaran).

https://doi.org/10.1016/j.jmapro.2023.01.068
Received 31 October 2022; Received in revised form 3 January 2023; Accepted 22 January 2023
Available online 2 February 2023
1526-6125/

instance, each Boeing 787 Dreamliner contains approximately 23 t of carbon fiber [1]. Owing to its multifarious advantages like light-weightiness, high strength reliability and aesthetics, carbon fiber often supersedes in preference when it comes to composite materials [10]. Manufacturing of carbon fiber is an energy intensive process and is produced using polyacrylonitrile (PAN) which is a synthetic thermoplastic that undergoes polymerisation resulting in high carbon footprint [1,12]. The industrial process of thermosetting and treatment adds to environmental cost by emitting high levels of carbon-based oxides along with other harmful gasses. Compared to stainless steel, carbon fiber has 40 % more embodied energy [13]. Being a composite, carbon fiber is inherently difficult to recycle [9,12]. Recently, environmental regulations and increase in awareness about eco-friendly materials has attracted various researchers to shift their focus to green composites or biocomposites [5]. Biocomposites materials are formed similar to carbon fiber composites by a matrix (resin) and fiber from biological origins [14]. The usage of biocomposites in industrial applications have enhanced due to their numerous advantages including lightweight, flexibility, cost-effectiveness, and the recyclability in nature [12,14]. Apart from these advantages, some mechanical properties of biocomposites particularly of flax fiber composites in terms of energy absorption have indicated remarkable outcomes. Yan *et al.* indicated that specific absorbed energy (SAE) and crush force efficiency (CFE) of flax-based composites were superior to conventional metal energy absorbers and close to that of glass/carbon fiber reinforced polymer composites making it a good candidate for crashworthy applications [15]. Further, flax fiber composites are also recommended as a viable candidate for applications that requires good sound and vibration properties as it indicated 51.03 % higher damping than the glass fiber reinforced composites [16]. Khandai *et al.* demonstrated that natural fiber is good in ductility and bending properties, however it is dependent on the lamination structure and environmental footprint particularly from moisture as water molecules act as a plasticizer in the cellulosic structure of natural fibers [17,18]. Hence, hybridisation of bio and synthetic composites could be considered as it would not only magnify the strength of both the elements but could be beneficial in terms of cost and environmental concerns compared to using 100 % synthetic composites [15,19].

As both type of materials, i.e., synthetic and natural composites result into carbon emissions, it is necessary to understand the impact of both the composites in environment to determine an alternative material/composite for future. Thus, life cycle assessment is required to analyse the environmental analysis and energy impact at each stage. This paper focuses on understanding the life cycle assessment of carbon fiber composites (CF composites) and bio-fiber composites prepared through one of the one of the most common manufacturing techniques called vacuum bagging.

2. Methodology

Composite manufacturing is an energy intense process which emits harmful gases at every stage of production [9]. The environmental and energy analysis in this paper was developed in compliance with the international standards ISO 14040 and ISO 14044 [20,21]. The LCA in this study was carried out considering the use-phase as well as end-of-life phase i.e., cradle to grave technique involving fiber production as well as recycling operations through GaBi [22].

2.1. Goal, scope & assumptions

The functional unit of the paper was defined as the production of 1 kg of carbon fiber composites prepared from PAN (Polyvinyl cyanide) fibers and biocomposites of flax fibers from the farms. The system boundaries for this paper are illustrated for carbon-fiber composites (Fig. 1) and biocomposites (Fig. 2). The locations for this LCA were considered in UK as its one of the major producers of flax fibers with some industries which manufacture PAN and carbon fibers composites as well. In this paper, certain assumptions were made as data for LCA were unable to be attained. For instance, CO_2 released/absorbed during vegetative cycles of plants were not estimated. It was assumed that the CO_2 was generated from the biomass and is equivalent to amount which was withdrawn from atmosphere during growth [4]. Further, the LCA results of the epoxy production have been ignored as the bio-based epoxy had less than 1.14 kgCO_2Eq. per ton and for small production quantity, it could be negligible.

2.2. Inventory analysis & impact assessment

The inventory for this study included a transportation range of 100 miles with other data from experimental studies and some from the literatures. These inventory data included energy consumptions for attaining flax fibers as well as the precursors and processes. Fig. 1

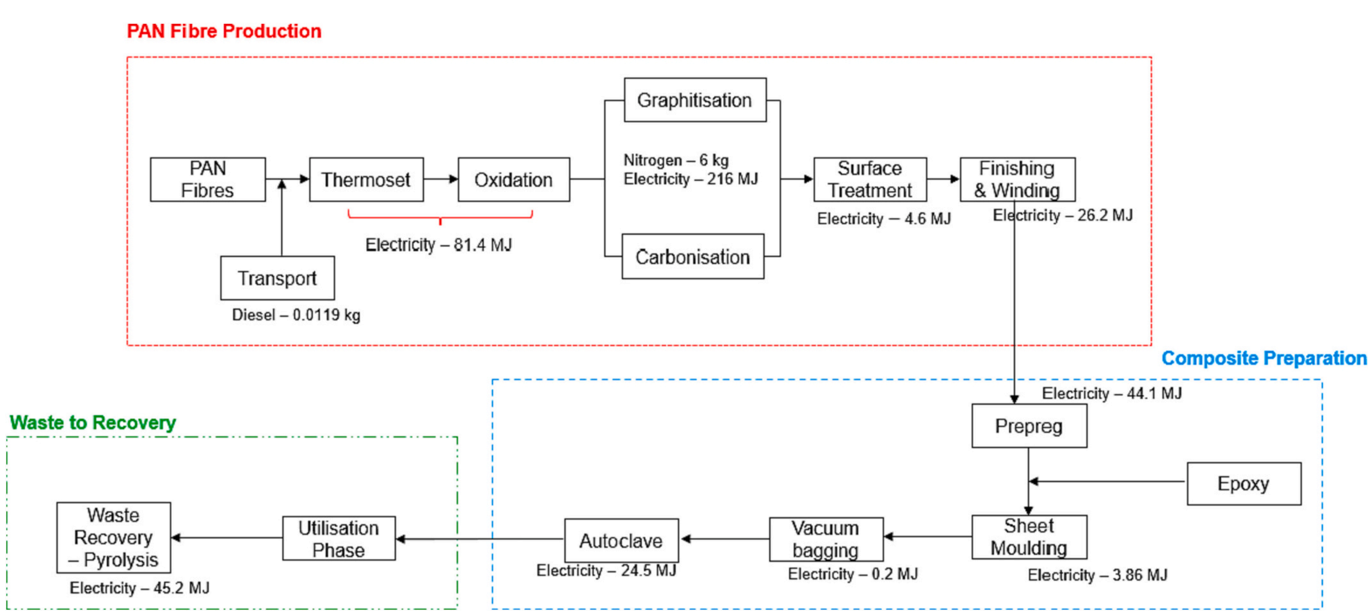

Fig. 1. Processing of carbon fiber composites from PAN fibers and its waste recovery.

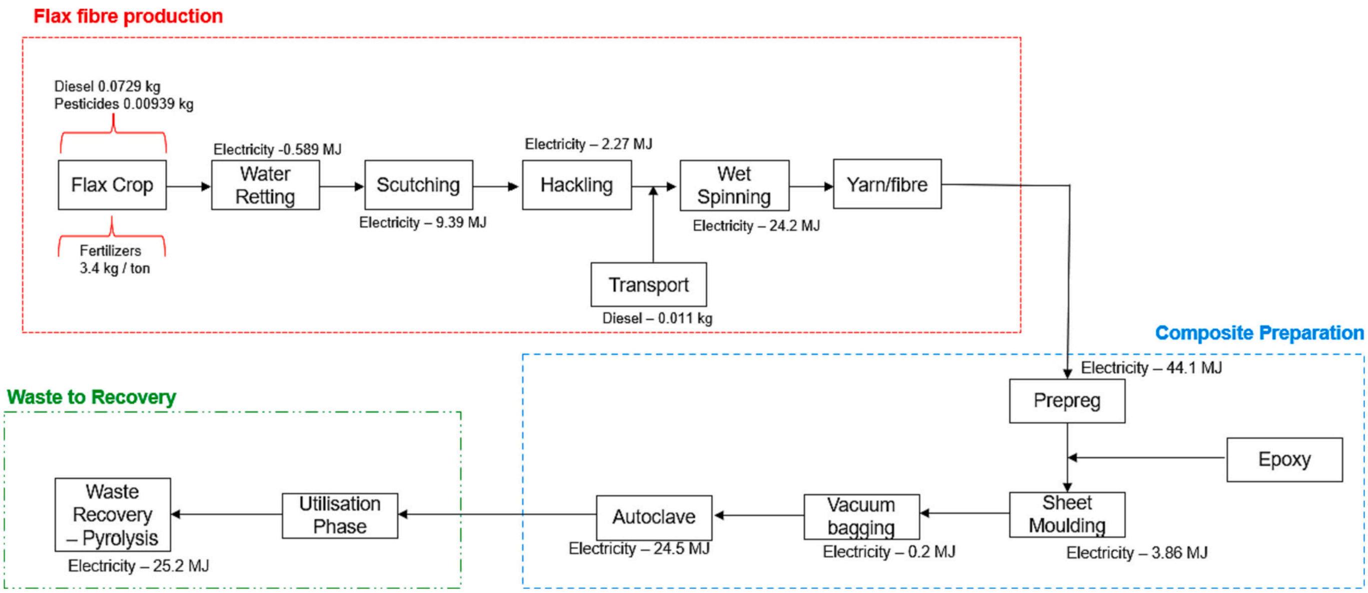

Fig. 2. Flax fiber production and biocomposites production along with its waste recovery through pyrolysis.

showcases the process involved in the carbon fiber composite production from the PAN fibers. The vacuum bagging technique details were measured at Kingston University London, and some data was attained from Groetsch et al. for fiber spinning [23]. Likewise, energy data for the flax fiber production were attained from Dissanayake et al. and composite production data were measured in house [24]. The impact assessment for this LCA were based on two methodologies including TRACI 2.0 (Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts) and CML-IA (Centre for Environmental Studies, University of Leiden) which analyse variety of emissions including global warming potential (GWP), acidification and eutrophication [25].

3. Results & discussion

The data interpretation part of life cycle assessment as per international standards is detailed in this section. The major environmental analysis such as GWP, acidification and eutrophication for biocomposites and carbon-fiber composites are discussed based on the attained results. Further effects to minimise these environmental impacts are also detailed. Additionally, the energy consumption of each process is detailed and ways to minimise them or sustainable are provided.

3.1. Environmental analysis

The carbon-fiber composites and flax fiber-based biocomposites were analysed for environmental analysis under different categories like GWP, acidification, human toxicity (cancer & non-cancer), respiratory inorganics, ecotoxicity and eutrophication in marine and freshwater environments. Each category was analysed based on a process flowchart illustrated in Figs. 1 and 2. Fig. 3 illustrates the results of environmental analysis carried for biocomposites and carbon composites. From the results it was determined that carbon fiber composites had ~5 times more environmental impact than flax-based biocomposites in mostly every emission scenario. This emission from carbon fiber composites could have been due to the process like carbonisation and graphitisation while producing carbon fibers. However, certain area like toxicity showcased higher values in biocomposites which could have been due to the use of fertilisers like nitrogen and phosphorus for growth of crops. The use of nitrogen and phosphorus could also affect the marine as well as eco-toxicity ranges as illustrated in Fig. 3.

Although the Fig. 3 details an overall environmental impact of carbon fiber and its counterpart, there is a need to understand effects onto the environment in detail to reduce the emissions. Thus, each process in the production of composites was analysed. GWP is a commonly known environmental concern which is calculated based on amount of CO_2 emitted into atmosphere [26]. Fig. 4 (left) illustrates the GWP of carbon

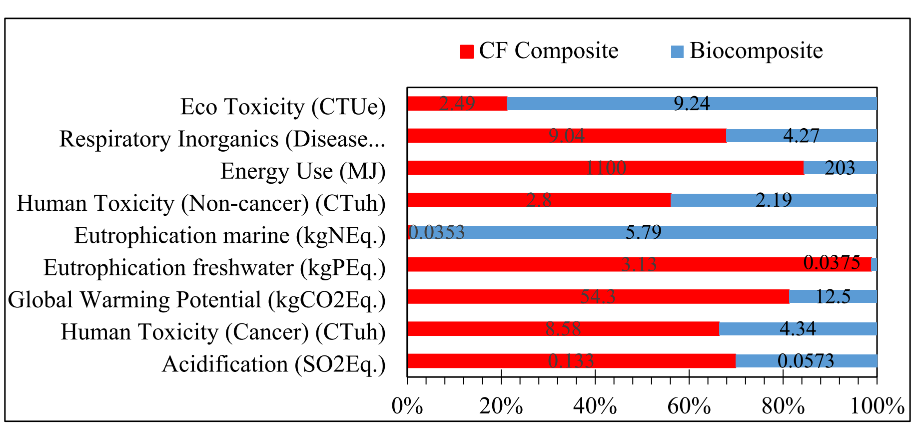

Fig. 3. Environmental analysis of carbon fibers composites and biocomposites.

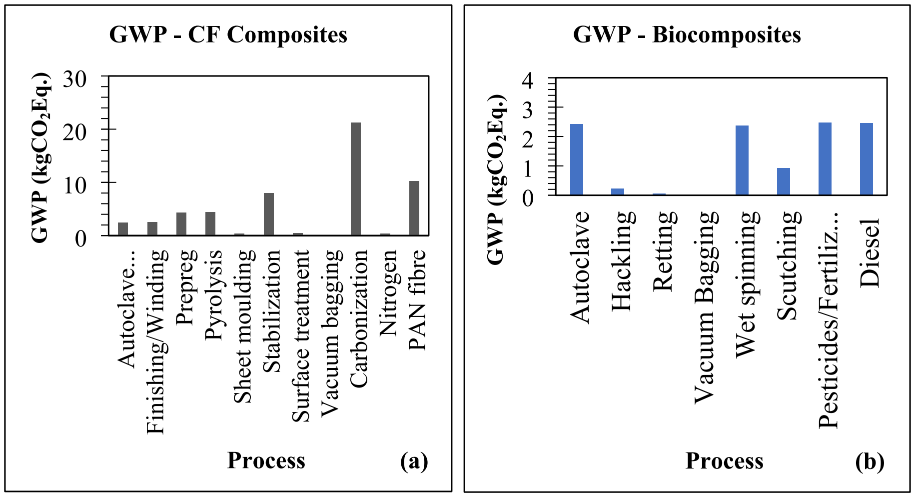

Fig. 4. GWP of vacuum bagged preparation of (a) carbon fiber composites and (b) biocomposites.

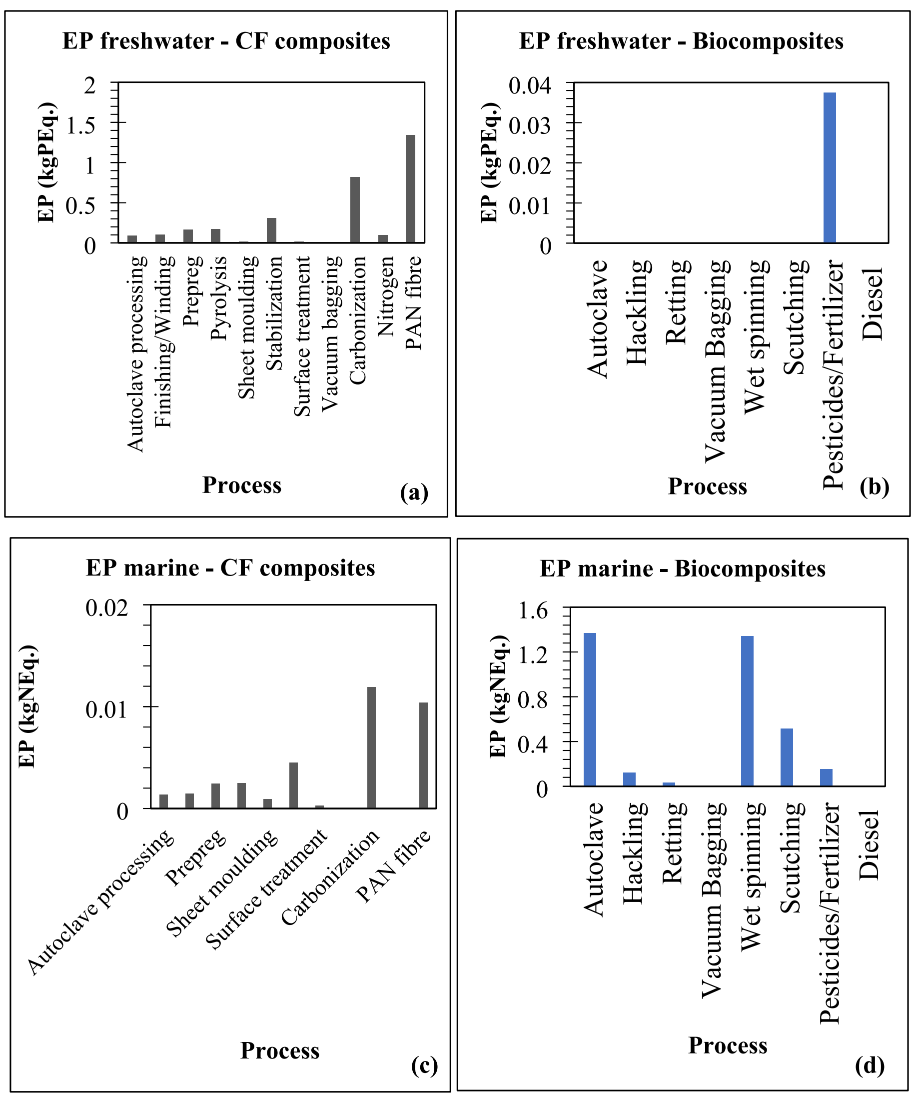

Fig. 5. Eutrophication of (a) carbon fiber composites in freshwater (b) biocomposites in freshwater (c) carbon fiber composites in marine and (d) biocomposites in marine.

fiber composites and it could be said that the carbonisation/graphitization was mostly responsible for the global warming gases owing to the dwell time in maintaining the furnace. Likewise, PAN fibers also indicated over 10.2 $kgCO_2Eq.$ which could have been emitted during its preparation or release of CO_2 while processing. On the other hand, biocomposites indicated pesticides and fertilisers as key reason for release of GWP along with autoclave process and wet spinning. This could be due to the flax cultivation where usage of inorganic fertilisers (Nitrogen, Phosphorus, Potassium) could result in nitrogen run off causing environmental impacts such as acidification, aquatic toxicity, human toxicity and eutrophication. Major sources of greenhouse gases which contribute to global warming and climate change are from energy used to power agricultural equipment and to produce and apply fertilisers and pesticides in flax fiber production. The Henfaes Research Centre suggests that for flax grown in UK, the levels of fertiliser are 40 kg/ha of nitrogen (N), 50 kg/ha of phosphorus (P) as P_2O_3 and 50 kg/ha of potassium (K) as K_2O are required. Likewise, in Northern Ireland (NI), suggested levels of fertiliser are 20 kg/ha N, 20 kg/ha P_2O_5 and 80 kg/ha K_2O respectively. Agricultural lime ($CaCO_3$) may be applied to maintain soil pH. The difference in the fertiliser level could affect the quality of the flax, and the environmental impact due to utilisation of the flax-based materials. Thus, a standardisation is required to support the flax production and control the environmental impacts.

Likewise, processing effects on the environmental factors like eutrophication in freshwater and marine environments are also illustrated in Fig. 5. The freshwater eutrophication of the carbon fiber composites was greater than that of biocomposites. The biocomposites affected the freshwater only through pesticides/fertiliser sources. However, carbon fiber composites affected the freshwater by emission from its original resource i.e., PAN fibers which could decompose by releasing cyanide during stabilisation process [17,27]. On the other hand, eutrophication emission in marine water was less in carbon fiber composites owing to its recyclability through pyrolysis. Also, biocomposites show exponential emission from wet spinning and autoclave processes; this could have been due to the formation of hydrocarbon sources which decomposes with increase in temperature.

Similar to eutrophication, human toxicity index and acidification rate of carbon fiber composites and biocomposites along with other toxicity values attained through environmental analysis are tabulated in Tables 1 and 2. From Table 1, it could be reported that the toxicity of the carbon-fiber composites was more dependent on the processing and behavior of PAN fibers through carbonisation process. The PAN fibers are generally toxic in nature owing to presence of cyanide which are formed while processing [28]. The PAN fibers alone without any processing had an ecotoxicity value of 1.22 CTUe and respiratory inorganics of 1.35. This is due to the chemical composition of PAN which contains complex polyamides which also gives a critical effect on cancer [29]. By analysing the results of carbon-fiber composite production through vacuum bagging, it could be said that the first two steps involving PAN processing had the highest environmental effects. Thus, it's required to modify this process to reduce global emissions which could be achieved by replacing the PAN fibers with amine or aromatic carboxylic acid-based materials which may potentially cut out the greenhouse emissions [30]. Use of these precursors may eliminate stabilisation phases which could further support in reducing the emissions.

On the other hand, From Table 2, it could be said that the maximum toxicity was associated with pesticides/fertilisers utilised in preparing the fibers which are the matrix of the biocomposites. These results are also supported by previous data which showcased that the use of pesticides in consistent way could lead to ecotoxicity up to a scale of 10 factors through extrapolation [31,32]. Other than pesticide, the toxicity values were also visible in use of diesel based non-renewable fossil fuels which is well established and research towards its alternatives are being carried out [33]. The use of non-renewable energy sources for agriculture could have also been responsible for the GWP increase in the biocomposites production. The GWP and toxicity of the biocomposites could be reduced by using renewable energy sources like solar or wind which could reduce in GWP values. Further, limiting or changing towards organic pesticides could also limit toxicity values on the nature. This research also excludes the environmental impacts of noise and vibration caused by the operation of large-scale agricultural equipment and fiber-processing gear.

3.2. Energy analysis

The total energy consumption in manufacturing processes vary relative to many factors such as type of process, location of the process, conditions assumed, types of requirements, equipment utilised, and technology utilised [34]. Fig. 6(a) & (b) show the breakdown of energy consumed in fabrication of both carbon fiber and biocomposites. It is evident that manufacturing of carbon fibers composites had the highest energy consumption of approximately 1100 MJ compared to biocomposite which consumed only 203 MJ. As clearly visible from Fig. 6 (a), the carbonisation and PAN fibers had the most energy consumption through carbon composite manufacturing followed by PAN treatment techniques. On the other hand, wet spinning and autoclave had the highest energy consumption in biocomposites. It is also worth mentioning that the energy consumed during carbonisation was higher than total energy utilised for manufacturing biocomposites. The energy consumed while manufacturing of biocomposites was still less than the end-of-life cycle assessment of carbon fiber composites including production of carbon fiber from PAN. By observing the energy and environmental impact of the initial steps like carbonisation and stabilisation it is evident that there is a need to develop a one stage thermal process to form carbon fibers. Various researchers have tried utilising the single thermal stages including pyrolytic recycling technology which have also been developed for aerospace applications [35,36]. Although pyrolytic techniques consumed high level of energy, it was able to recover over 98 % in various experimental works making them a more suitable operation to recycle carbon fiber composites [37,38].

Comparably, biocomposites showcased limited energy consumption including its agriculture phases. The energy impact of biocomposites

Table 1
Different toxicity emissions from carbon-fiber composites.

Processing technique	Acidification (SO_2 Eq.)	Human toxicity cancer (CTUh)	Human toxicity non-cancer (CTUh)	Respiratory inorganics (diseases incidence)	Ecotoxicity (CTUe)
Autoclave	0.00612	0.183	0.12	0.419	0.693
Finishing/winding	0.00654	0.196	0.128	0.448	0.074
Prepreg	0.011	0.338	0.215	0.753	0.124
Pyrolysis	0.0113	0.338	0.221	0.772	0.128
Sheet moulding	0	0	0.0189	0.0659	0.0109
Stabilisation	0.0203	0.609	0.398	1.39	0.23
Surface treatment	0.00115	0	0.0225	0.0786	0.013
Vacuum bagging	0	0	0	0.003	0
Carbonisation	0.0539	1.62	1.06	3.69	0.61
Nitrogen	0	0	0.0135	0.0672	0.0163
PAN fiber	0.0206	5.2	0.602	1.35	1.22

Table 2
Different toxicity emissions from flax based biocomposites.

Processing technique	Acidification (SO_2 Eq.)	Human toxicity cancer (CTUh)	Human toxicity non-cancer (CTUh)	Respiratory Inorganics (Diseases incidence)	Ecotoxicity (CTUe)
Autoclave	0.00617	0.0185	0.121	0.422	0.0698
Hackling	0.000567	0	0.011	0.0388	0
Retting	0.000147	0	0	0	0
Vacuum bagging	0	0	0	0	0
Wet spinning	0.00605	0.0181	0.118	0.414	0.0684
Scutching	0.00234	0	0.0459	0.16	0
Pesticides/fertiliser	0.03182	4.26	1.69	0	0
Diesel	0	0	0	2.525	8.93

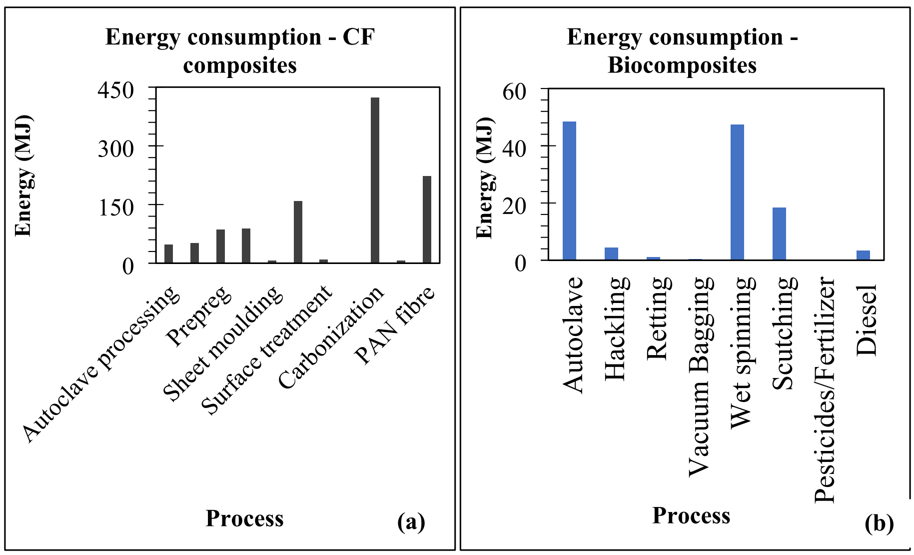

Fig. 6. Energy consumption analysis of (a) carbon fiber composites and (b) biocomposites.

was mostly on the autoclave technique where the composites were placed for curing to harden and wet spinning technique where the fiber were created. However, the attained energy results were limited as the evaluation of harvesting and cultivation of flax fibers related data were very limited. The calculation based on direct agricultural area for flax fiber may be different than the real area. This indirect land usage may have certain tolerance effects on the life cycle assessment methodology which could quantify both LCA measurements and results impacts [39].

3.3. Waste recovery

The recovery technique utilised in both the process involve pyrolysis which has also shown energy consumption of 8 % from total energy consumption by carbon fiber composite. Depending on the temperature of fluidized bed, decomposition products may lead to release NOx and other chemicals in case of both carbon and flax fiber composites. There is also the possibility of dioxins being produced if chlorine is present [40]. As a result of NOx, there may be repercussions in terms of acidification, human and aquatic toxicity, and ultimately eutrophication and other environmental impact metrics, such as land use, acidification, ozone depletion, human and eco-toxicity, may be included into future research [41]. Air emissions are also particularly crucial for the transportation industry, which is why future research might compare the emissions from CFRP recycling with reductions during the usage phase achieved via lower fuel use. Emissions from the recycling process might also be better understood when measurement data is available since the study being conducted right now was based on stoichiometric balances of carbon [23,42].

3.4. Transition to bio-economy

The negative impact of utilising bio-based materials that could arise from transitioning towards new bioeconomy in the future is not considered in any aspects of the LCA although use of bio-based material may lead to increase in prices of food-based products and land usage. There are also several challenges that need to be overcome to properly integrate LCA into innovation and development to better understand transition to bioeconomy [20]. Although bio-products are environmentally exceptional compared to fossil products in some life cycle impact categories, while the scenario is often contradictory in others [1,9,43,44]. This could be due to the highly diverse group of bio-products and its environmental impacts relative to their fossil counterparts is case specific and very much dependent on the feedstock utilised [45]. Though, there have been various research on the bio-products, it is difficult to gauge the sustainability of biocomposites as these studies does not addressed the system holistically and have not considered research gaps such as fair share of resources, rates of exploitation that are renewable, environmental thresholds and buffering capacity, balanced consumption and circularity [42,43,46,47]. The transition to bioeconomy requires more than simply replacing carbon as it is a complex and irreversible adaptation of the whole system, which involves innovation, new lifestyles, and changes to governance [45,48].

4. Conclusion

The life cycle assessment was carried out for carbon-fiber composites and flax based biocomposites to analyse and estimate the environmental impact as well as energy impact with certain assumptions. The most well-known technique of composite manufacturing i.e., vacuum bagging was chosen as a fabrication technique for both the composites. The environmental and energy impact was accessed for fabricating 1 kg of the composite with bio-resin. The outcomes of analysis indicated that biocomposites production consumes about 202 MJ/kg whereas carbon fiber composites required over 5 times (1100 MJ/kg) than bio-composites owing to complex processes as carbonisation. The production of carbon-fibers from PAN medium though different techniques resulted in 50 % of overall energy consumption. Likewise, in bio-composites, wet spinning of biocomposites resulted in same amount of energy consumption. Carbon fiber composites also resulted in ~54 $kgCO_2Eq.$ total global warming potential (GWP) which was about ~4.5 times more than biocomposites (12 $kgCO_2Eq.$) and other emissions were likewise higher than biocomposites except in certain scenarios. This release could have been a direct correlation with release of carbon-based oxides while processing the carbon-fibers. Being a bio-carbon itself most of the flax-based fiber composites retained its cellulose activities into the resin leading to reduced release while processing. This paper provided the importance of orienting ourselves to the fibers-based biocomposites which may serve as replacement towards carbon-fiber composites to reduce emission in future, properties of standalone flax-based composites are still being explored. This is because of the mechanical stability of flax biocomposites is highly vulnerable and dependent on environmental footprints, particularly moisture.

Hence further work is required to be carried out to strengthen and sustain the rigidity of the composite. Furthermore, the amount of fiber crop production necessary to replace the carbon fiber industries require huge land occupancy with various energy source requirements. Thus, changing agricultural needs and energy sources to renewable would be another challenge ahead.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

Authors would like to acknowledge the support from Kingston University, London towards this research.

References

[1] Arockiam NJ, Jawaid M, Saba N. Sustainable bio composites for aircraft components. SustainComposAerospApplic 2008:109–23.
[2] Sun X, Wang P, Ferris T, Lin H, Dreyfus G, Gu B-H, Zaelke D, Wang Y. Fast action on short-lived climate pollutants and nature-based solutions to help countries meet carbon neutrality goals. AdvClimChangRes 2022;13(4):564–77.
[3] Huang W, Chen W, Anandarajah G. The role of technology diffusion in a decarbonizing world to limit global warming to well below 2 °C: an assessment with application of global TIMES model. Appl Energy 2017;208:291–301.
[4] Rosa AL, Cozzo G, Latteri A. Life cycle assessment of a novel hybrid glass-hemp/thermoset composite. J Clean Prod 2013;44:69–76.
[5] Das R, Samantha B, Bhattacharjee C. Traditional biomass: a replacement for petro-fuels. In: Encyclopedia of renewable and sustainable materials. 3; 2020. p. 795–809.
[6] Yaghoobi H, Fereidoon A. Preparation and characterization of short kenaf fiber-based biocomposites reinforced with multi-walled carbon nanotubes. ComposPart 2019;162:314–22.
[7] Liu N, Wang Y, Bai Q, Liu Y, Wang P, Xue SYQ, Li Q. Road life-cycle carbon dioxide emissions and emission reduction technologies: a review. JTrafficTranspEng (EnglEd) 2022;9(4):532–55.
[8] Karlsson I, Rootzen J, Johnsson F, Erlandsson M. Achieving net-zero carbon emissions in construction supply chains – a multidimensional analysis of residential building systems. DevBuild Environ 2021;8(100059):1–21.
[9] Czapla A, Ganesapillai M, Drewnowski J. Composite as a material of the future in the era of green deal implementation strategies. Processes 2021;9(2238):1–20.
[10] Biswas MR, Biswas AK. The global environment: past, present and future. ResourPolicy 1985;11(1):25–42.
[11] Sun W, Wei X, Zhou B, Lu C, Guo W. Greenhouse heating by energy transfer between greenhouses: system design and implementation. Appl Energy 2022;325:119815.
[12] Amaechi CV, Agbomerie CO, Orok EO, Ye J. Economic aspects of fiber reinforced polymer composite recycling. In: Encyclopedia of renewable and sustainable materials. 2; 2020. p. 377–97.
[13] Der A, Dilger N, Kaluza A, Creighton C, Kara S, Varley R, Herrmann C, Thiede S. Modelling and analysis of the energy intensity in polyacrylonitrile (PAN) precursor and carbon fibre manufacturing. J Clean Prod 2021;303:127105.
[14] An B, Sun W. A theory of biological composites undergoing plastic deformations. J Mech Behav Biomed Mater 2019;93:204–12.
[15] Yan L, Chouw N. Crashworthiness characteristics of flax fibre reinforced epoxy tubes for energy absorption application. MaterDes 2013;51:629–40.
[16] Prabhakaran S, Krishnaraj V, Kumar MS, Zitoune R. Sound and vibration damping properties of flax fiber reinforced. Procedia Eng 2014;97:573–81.
[17] Upadhyayulu VK, Gadhamshetty V, Athanassiadis D, Tysklind M, Meng F, Pan Q, Cullen J, Yacout D. Wind turbine blades using recycled carbon fibers: an environmental assessment. Environ Sci Technol 2022;56(2):1267–77.
[18] Khandai S, Nayak R, Kumar A, Das D, Kumar R. Assessment of mechanical and tribological properties of flax/kenaf/glass/carbon fiber reinforced polymer composites. MaterTodayProc 2019;18:3835–41.
[19] Umapathi D, Devaraju A, Harikumar R. Exploration of mechanical properties of flax fibre and GFRP hybrid composites. Mater Today Proc 2021;39(Part 1):875–8.
[20] Bachmann TM. Towards life cycle sustainability assessment: drawing on the NEEDS project's total cost and multi-criteria decision analysis ranking methods. Int J Life Cycle Assess 2013;18:1698–709.
[21] Heijungs R. Ten easy lessons for good communication of LCA. Int J Life Cycle Assess 2014;19. 473-376.
[22] GaBi. GaBi: software and database contents for Life Cycle Engineering. Stuttgart: PE INTERNATIONAL AG; May 2022.
[23] Groetsch T, Creighton C, Varley R, Kaluza A, Der A, Cerdas F, Herrmann C. A modular LCA/LCC-modelling concept for evaluating material and process innovations in carbon fibre manufacturing. Procedia CIRP 2021;98:529–34.
[24] Dissanayake NP, Summerscales J, Grove S, Singh M. Energy use in the production of flax fiber for the reinforcement of composites. JNatFibres 2009;6(4):331–46.
[25] Bare J. TRACI 2.0: the tool for the reduction and assessment of chemical and other environmental impacts 2.0. Clean TechnolEnvironPolicy 2011;13:687–96.
[26] Makhnatch P, Khodabandeh R. The role of environmental metrics (GWP, TEWI, LCCP) in the selection of low GWP refrigerant. Energy Procedia 2014;61:2460–3.
[27] Damodaran S, Desai P, Abhiraman A. Chemical and physical aspects of the formation of carbon fibres from PAN-based precursors. JTextInst 1990;81(4):384–420.
[28] Edie D. The effect of processing on the structure and properties of carbon fibers. Carbon 1998;36(4):345–62.
[29] Kumar N, Natrayan L, Kasirajan G, Kaliappan S, Kamal M. Development of novel bio-mulberry-reinforced polyacrylonitrile (PAN) fibre organic brake friction composite materials. Bioinorg Chem Appl 2022;2022(6426763):1–11.
[30] Sakamoto K, Kawajiri K, Hatori H, Tahara K. Impact of the manufacturing processes of aromatic-polymerbased carbon fiber on life cycle greenhouse gas emissions. Sustainability 2022;14(3541):1–15.
[31] Margni M, Rossier D, Crettaz P, Jolliet O. Life cycle impact assessment of pesticides on human health and ecosystems. Agr Ecosyst Environ 2002;93(1–3):379–92.
[32] Eddleston M. Poisoning by pesticides. Medicine 2020;48(3):214–7.
[33] Lankoff A, Brzoska K, Czarnocka J, Kowalska M, Lisowska H, Mruk R, Overevik J, W-Ciuk A, Zuberek M, Kruszewski M. A comparative analysis of in vitro toxicity of diesel exhaust particles from combustion of 1st- and 2nd-generation biodiesel fuels in relation to their physicochemical properties—the FuelHealth project. EnvironSciPollutRes 2017;24:19357–74.
[34] Menezes A, Cripps A, Buswell R, Wright J, Bouchlaghem D. Estimating the energy consumption and power demand of small power equipment in office buildings. Energy Build 2014;75:199–209.
[35] Das S. Life cycle assessment of carbon fiber-reinforced polymer composites. Int J Life Cycle Assess 2011;16:268–82.
[36] Jody BJ, Joseph EJD, Pomkala Jr A, Greminger JL. A process to recover carbon fibers from polymer-matrix composites in end-of-life vehicles. JOM 2004;56:43–7.
[37] Pakdel E, Kashi S, Varley R, Wang X. Recent progress in recycling carbon fibre reinforced composites and dry carbon fibre wastes. ResourConversRecycl 2021;166(105340):1–20.
[38] Rani M, Choudhary P, Krishnan V, Zafar S. A review on recycling and reuse methods for carbon fiber/glass fiber composites waste from wind turbine blades. Compos Part B 2021;215(108768):1–15.
[39] Ita-Nnagy D, V-Rowe I, Kahhat R, Quispe I, C-Carrasco G, Clauser NM, Area M. Life cycle assessment of bagasse fiber reinforced biocomposites. SciTotal Environ 2020;720(137586):1–12.
[40] McKay G. Dioxin characterisation, formation and minimisation during municipal solid waste (MSW) incineration: review. Chem Eng J 2002;86(3):343–68.
[41] Verma R, Vinoda KS, Papireddy M, Gowda ANS. Toxic pollutants from plastic waste- a review. Procedia EnvironSci 2016;35:701–8.
[42] El-Chichakli B, Braun JV, Lang C, Barben D, Philp J. Policy: five cornerstones of a global bioeconomy. Nature 2016;535:221–3.
[43] D'Amato D, Gaio M, Semenzin E. A review of LCA assessments of forest-based bioeconomy products and processes under an ecosystem services perspective. Sci Total Environ 2020;706:135859.
[44] Walker S, Rothman R. Life cycle assessment of bio-based and fossil-based plastic: a review. J Clean Prod 2020;261(121158):1–15.
[45] Talwar N, Holden NM. The limitations of bioeconomy LCA studies for understanding the transition to sustainable bioeconomy. Int J Life Cycle Assess 2022;27:680–703.

[46] Wohlfahrt J, Ferchaud F, Gabrielle B, Godard C, Kurek B, Loyce C, Therond O. Characteristics of bioeconomy systems and sustainability issues at the territorial scale. A review. J Clean Prod 2019;232:898–909.
[47] Strategy UB. A sustainable bioeconomy for Europe: strengthening the connection between economy, society and the environment. Copenhagen: European Commission; 2018.
[48] Beigbeder J, Soccalingame L, Perrin D, Bénézet J-C, Bergeret A. How to manage biocomposites wastes end of life? A life cycle assessment approach (LCA) focused on polypropylene (PP)/wood flour and polylactic acid (PLA)/flax fibres biocomposites. Waste Manag 2019;83:184–93.