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Organosolv lignin carbon fibers and their prospective application in wind turbine blades: An environmental performance assessment

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ABSTRACT

Lignin is a potential sustainable alternative to polyacrylonitrile (PAN) precursor for the production of carbon fibers. The high purity lignin extracted from residual forest biomass via organosolv process undergoes stabilization and carbonization treatment to produce carbon fibers. Recent developments suggest the potential of producing organosolv lignin carbon fibers (OLCF) with competing mechanical properties similar to PAN carbon fibers. This is likely to enable the use of OLCF in structurally demanding applications such as wind turbine blades. In this work, a life cycle assessment (LCA) is performed with a threefold objective. First, the environmental footprint of OLCF is quantified and results are compared with PAN-CF produced in Sweden and elsewhere in Europe i.e., electricity demands met by European average electrical grid (RER). Second, the environmental performance of OLCF reinforced wind turbine blades (referred as BIOMAT) to be installed in 0.8 MW capacity is evaluated against incumbent variants: glass fiber turbine blade (GFTB), PAN-CF based turbine blades manufactured in Sweden (CFTB-SE), and other parts of Europe (CFTB-RER). Finally, the total environmental externality costs (EEC) of these blades and corresponding lifetime electricity generation when they are installed in 0.8 MW capacity wind turbine blade are calculated. Our results indicate that the environmental impacts of OLCF are lower by 71–94% than PAN-CF-RER in nine, and lower by 43–90% than PAN-CF-SE in six out of ten impact categories quantified respectively. BIOMAT blades also have better overall environmental performance than existing blade variants and particularly lucrative because of their negative total climate change impact. The total EEC of BIOMAT blades is 74%, 83% and 88% lower than GFTB, CFTB-SE and CFTB-RER respectively. Correspondingly, the total EEC of lifetime electricity generated by wind turbine equipped with BIOMAT blades is 11%, 17% and 23% lower than the respective blade variants.

1. Introduction

Lignin is an abundant, but underutilized, carbon rich biopolymer found in the cell walls of trees and plants. Recently, lignin has been identified as an important precursor for synthesis of carbonaceous materials, especially carbon fibers (Bengtsson, 2019; Bengtsson et al., 2019; bioplastics, 2019; Chang et al., 2017; Chatterjee and Saito, 2015; Fang et al., 2017; Mainka et al., 2015; Souto et al., 2018). Polyacrylonitrile (PAN) based carbon fibers (PAN-CF) are commonly used as a strength bearing reinforcement into polymeric materials. PAN-CF polymer composites offer a wide range of industrial applications such as manufacturing of lightweight automotive components, wind turbine blades and airplane fuselage. However, PAN-CF suffers from high production costs, attributed to the energy intensity of PAN precursor production, and poor recyclability at the end of life. To overcome these challenges, lignin has been identified as an alternative precursor for CF synthesis because it can be sourced from low cost renewable feedstock sources such as residues from the forest or agriculture industries.

Pure lignin can be obtained when the lignocellulosic structural linkages within cell walls of plant biomass are enzymatically or chemically broken, separating lignin from the cellulose and hemicellulose, either in the form of solid or as liquor which is eventually purified

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(Chatterjee and Saito, 2015). Organosolv, a chemical treatment based fractionation method developed to delignify plant biomass, has received widespread attention in recent years due to its higher efficiency in separating lignin compared to other techniques (Matsakas et al., 2018). Although the conventional organosolv process is able to recover lignin even from recalcitrant biomasses, such as softwood, fractionation is not achieved completely as significant amount of lignin is still associated with the cellulose stream (Matsakas et al., 2018; Nitsos et al., 2018). This issue is addressed in our recent studies where we demonstrated that a hybrid process combining organosolv and steam explosion can efficiently fractionate woody biomass (birch and spruce) into lignin, cellulose and hemicellulosic streams (Matsakas et al., 2018, 2019). The fractionated cellulose, hemicellulose and lignin can be used for a wide range of applications, including the production of renewable energy, materials and chemicals. One example of lignin application within the materials field is the production of organosolv lignin carbon fibers (OLCF), a high valued intermediate material with potential application in multiple industrial sectors. Cellulose and hemicellulose can be considered as feedstock for anaerobic digestion to produce biogas that be used as energy source for the organosolv plant or as vehicle fuel after being upgraded.

In this LCA study, we evaluated the sustainability prospects of OLCF manufactured wind turbine blades in comparison with their market incumbent counterparts i.e., glass fiber (GF) and PAN-CF based wind turbine blades. A few LCA studies evaluating the environmental performance of wind turbine blades have been reported in literature (Liu and Barlow, 2016; Tomoporowski et al., 2018). These LCAs are focused on quantifying the environmental impacts of wind turbine blades fabricated by using existing materials, i.e. glass and carbon fiber reinforced polymer composites (Haapala and Prempreeda, 2014; Ozoemena et al., 2018; Razdan and Garrett, 2015). Some studies also discussed the environmental performance of the entire wind turbine, including its energy payback period (Haapala and Prempreeda, 2014; Razdan and Garrett, 2015). Carbon fibers obtained from lignin precursors are currently not considered for structural applications including wind turbine blades. But owing to the recent developments (explained in the next section), the feasibility of their introduction into the wind energy industry cannot be ruled out. Therefore, the findings of this LCA work offer critical insights on the environmental performance of OLCF based wind turbine blades in comparison to popular market incumbent options. To the best of our knowledge, no previous studies exist on sustainability assessment of OLCF based wind turbine blades and therefore, our current work aims to fill that gap in open literature.

2. Feasibility of using organosolv lignin carbon fibers for manufacturing wind turbine blades

The prospects of LCF entry into wind energy industry must be understood panoramically. Technical, environmental and economic feasibility considerations as highlighted in Fig. 1 are important to facilitate informed decisions on possible utilization of LCF as candidate material for manufacturing wind turbine blades.

Research efforts are underway to improve mechanical properties of lignin carbon fibers (LCF) and bring them to the competitive landscape of strength bearing materials used for structural applications such as manufacturing of wind turbine blades (Bai et al., 2024; Black, 2016; Braitmaier, 2019; Luo et al., 2021, 2024). LCF is considered as a promising and sustainable alternative for CF produced from PAN precursor. Today, incorporation of LCF as a structural reinforcement into wind turbine blades is not a commercial reality because their mechanical properties are inferior compared to PAN-CF. Poor mechanical performance of LCF because of using lignin precursor itself and more specifically attributed to inherent molecular construct of lignin (Bai et al., 2024; Luo et al., 2024). Lignin molecules, because of their heterogenous and highly polydisperse nature had failed to reach structural alignment expectations (as observed in PAN-CF) required to yield LCF with high tensile properties (Bai et al., 2024; Luo et al., 2024). However, the recent developments on the using lignin in such applications, paint a bright picture as the possibility of producing LCF with the mechanical properties competent to be used in structural applications such as wind turbine blade has been successfully demonstrated by some research groups (Bai et al., 2024; Luo et al., 2024).

Organosolv lignin obtained from hardwood (e.g., birch, maple) is preferred as a precursor for high valued CF production because of its thermal mobility and for manufacturing reasons such as better spinnability (Azega et al., 2023; Hosseinaei et al., 2017). LCF produced from

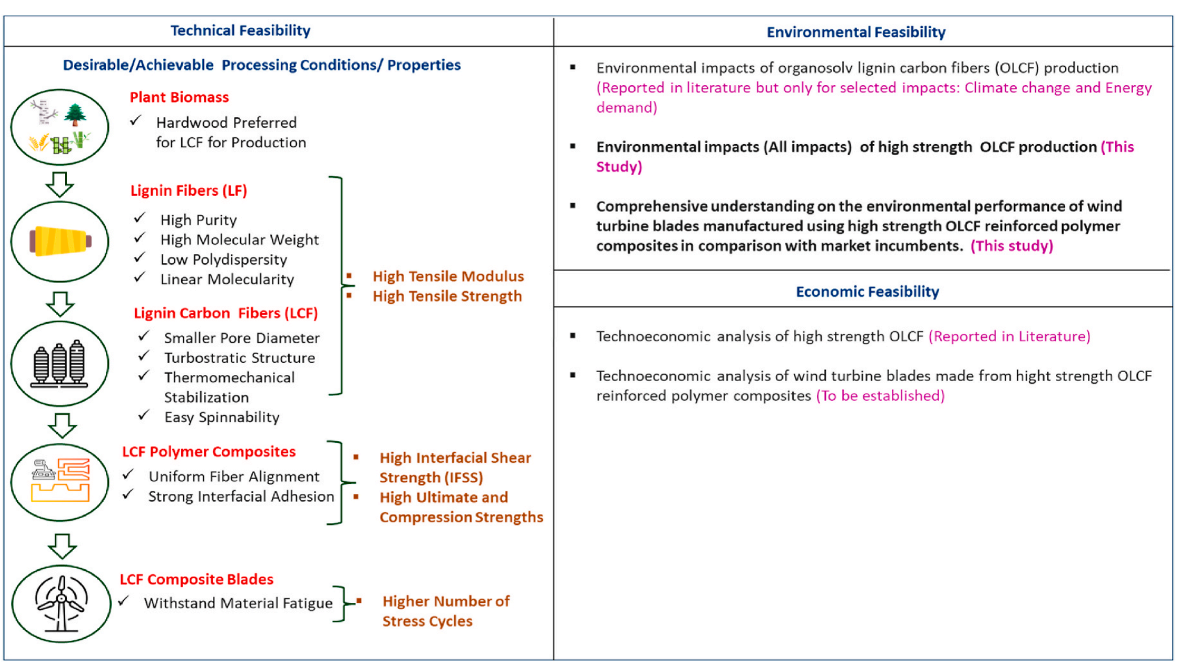


Fig. 1. Technical, environmental and economical feasibility considerations for production of OLCF incorporated wind turbine blades (Icons are free icons obtained from Flaticon (Flaticon, 2024).

(especially using hardwood biomass sources) organosolv lignin (OLCF) through melt spinning technique (owing to its numerous benefits like no solvent use, no diffusion and low cost (Wang et al., 2022)) exhibit mechanical properties (i.e., tensile strength of 2456 MPa and tensile elastic modulus of 236 GPa (Bai et al., 2024; Luo et al., 2024)) on par with standard elastic modulus grade PAN-CF (with tensile strength of 2500 MPa and tensile module ranging between 200 and 280 GPa (EpsilonComposite, 2024; JCPA, 2024; Zoltek, 2021)). On the other hand, the tensile modulus of OLCF reported in these works (Bai et al., 2024; Luo et al., 2024) is three times higher, and tensile strength is 70% of that of the glass fibers (JPS, 2021). The outcome of these studies suggests that high strength OLCF can be produced by following a unique thermomechano-chemical approach during stabilization and carbonization steps. This involves thermal stabilization cum carbonization of lignin fibers at 700 °C and simultaneously subjecting them to controlled stretching by applying mechanical tension. Increase in mechanical properties of LCF by applying external tension (linear stretching with external force) is also confirmed by other authors (Bengtsson et al., 2019, 2022; Yang et al., 2023). Thus with thermomechanical method, branched chains and weaker (more oxygen containing) bonds from lignin molecules are removed from lignin molecules, thereby enabling them to realign themselves into a isotropic and more turbostratic structure (similar to PAN-CF) responsible for production of LCF with higher tensile properties (Bai et al., 2024; Luo et al., 2024). Furthermore, smaller pore sized OLCF (1.99 mm) can be produced with this method which is a critical development from for formulation OLCF polymer composites. This is because the fibers with larger pore sizes are more progressive in introducing cracks and defects in polymer composite than their smaller pore sized counterparts (Bai et al., 2024; Luo et al., 2024).

While production of structural grade OLCF is a milestone in itself, the true potential of its use as strength bearing reinforcement will only be unveiled when OLCF polymer composites are tested and deemed fit for structural applications. At the moment, only a handful studies are published in the literature that disclose mechanical properties of LCF polymer composites. From these studies, the mechanical properties are found to be inferior to consider LCF polymer composites for structural applications. But with the most recent demonstration of OLCF production by placing an emphasis on optimized thermomechano-chemical approach, it is plausible to argue that fabrication of OLCF reinforced polymer composites with high tensile properties is close to reality. Also, another and probably most important conclusions from studies on lignin carbon fiber composites (Harper et al., 2018; Meek et al., 2016) is that the interfacial shear strength (IFSS) of LCF reinforced polymer composites is stronger than PAN based polymer composites. In their experiments, it was observed that fiber does not disengage from the polymer matrix in spite of interfacial damage signifying high IFSS (Harper et al., 2018). The IFSS is observed to be higher for LCF reinforced into epoxy composites, especially when epoxy resin obtained from biobased sources (e.g., pine oils) (Harper et al., 2018). In addition, the strain at break of OLCF epoxy composites is 0.74–1.6% (Harper et al., 2018) and similar to PAN-CF epoxy composites (Natio et al., 2009; Shimadzu, 2019). Thus, with IFSS higher than PAN CF polymer composites(Harper et al., 2018) and with a sighting possibility to improve tensile properties (through reinforcement of OLCF from optimized thermomechanical method), OLCF reinforced polymer composites can qualify for structural applications.

Assuming that OLCF reinforced polymer composites gain competency in coming years and replace PAN based counterparts in production of wind turbine blades, one major challenge that still remains is the lifetime of these blades. The idea of using OLCF polymer composites for wind turbine blades may be rigorously scrutinized because of absence of simulation data calculating their lifetime. Fatigue failure is one among many causes responsible for premature termination of wind turbine blades and directly attributed to strength of fiber composites subjected to cyclic stress (Mishnaevsky-Jr, 2022). As a preliminary estimate, the number of permissible load cycles to failure of a wind turbine blade can be quantified by Goodman method obtained from literature(Loza et al., 2019; Muyan and Coker, 2020) using equation (1).

$$N_f = \left[\frac{UTS_c + |UCS_c| - |2 \bullet \gamma_{ma} \bullet \sigma_m - UTS_c + |UCS_c||}{2 \bullet \left(\frac{\gamma_{mb}}{C_i} \right) \bullet \sigma_{amp}} \right]^m \tag{1}$$

Where,

N_f = number of stress cycles to failure

UTS_c = Ultimate tensile strength of composite

UCS_c = Ultimate compression strength of composite (negative stress)

γ_{ma}, and γ_{mb}, and C_i are safety factors (Typically, $\gamma_{ma} = 2.406$; $\gamma_{mb} = 1.906$ and C_i for uni-directional reinforcement = 1)

σ_m and σ_{amp} are mean and amplitude for given number of cycles and given stress ratio (defined as R = minimum cyclic stress/maximum cyclic stress)

m = 10 for composites with epoxy resin.

UTS_c and UCS_c for PAN CF epoxy composites (Unidirectional (0°)) are 1000 and 850 MPa respectively (Thawre et al., 2011). From the constant fatigue life diagram for carbon fiber epoxy composites developed by the authors (Thawre et al., 2011)), the reported σ_m and σ_{amp} values at a stress ratio of 0.5 (i.e., in fiber dominated tension-tension stress regime are 400 and 100 MPa respectively). Thus, substituting the values in equation (1), N_f for PAN-CF epoxy composite = 1.09E+09 cycles. As a ballpark estimate, even if OLCF epoxy composites has 35% lower UTS_c (650 MPa) and 41% lower UCS_c (520 MPa) than PAN-CF composites, N_f will be equal to 1.03E+08 cycles. Today, wind turbines operate with an the N_f value between 10^8-10^9 cyclic stress cycles (Bustamante et al., 2015) which means OLCF polymer composite based wind turbine blades have highly likely probability to last for full lifespan of 20 years.

We realize that utilization of OLCF in wind turbine blades is still at conceptual stage and several bottlenecks needs to be addressed before warranting the application of OLCF polymer composites for manufacturing wind turbine blades. But ongoing research efforts are suggestive of rapid technological progress that is paving a way for market readiness of structurally ready OLCF polymer composites. Therefore, it is valuable to commission an environmental assessment study to gain early insights of using OLCF polymer composites in wind turbine blades.

Environmental feasibility is the second leg of threefold feasibility studies (Fig. 1) that is aimed to develop comprehensive understanding on the environmental benefits and tradeoffs of using wind turbine blades manufactured from OLCF polymer composites in comparison with market incumbents. A survey of relevant literature reveals that dearth of LCA studies on using LCF polymer composites in structural applications such as wind turbine blades. Few LCAs are available on production of LCF and LCF polymer composites. Environmental performance of carbon fibers produced from Kraft (Janssen et al., 2019) and organosolv lignin (Das, 2011; Hermansson, 2020; Hermansson et al., 2019) are published by some authors. However, these studies especially on OLCF production have only reported climate change impact ranging between 17 and 24 kg CO_2/kg (Das, 2011; Hermansson, 2020; Obasa et al., 2022) and cumulative primary energy demand around 670 MJ/kg LCF respectively (Das, 2011). Only one study evaluated environmental performance of OLCF polymer composites (Das, 2011) but the focus was mainly on climate change and cumulative energy demand impact categories. Moreover, the precursor processing route for OLCF production (organosolv process, acid catalyzed) and geographical boundary (USA) considered for carbon fiber production in this work are both different from our current LCA. In this study, we not only analyzed and reported complete impact spectrum for OLCF, but also conducted a detailed environmental performance assessment on its potential use in high valued applications such as wind turbine blades.

Finally, the economic feasibility of OLCF production via thermomechano-chemical method is also studied and reported as $9.19 per kg which is 33% lower compared to cost of $13.72 per kg of PAN-CF production (Luo et al., 2024). However, the technoeconomic feasibility analysis of OLCF polymer composites and their application in wind turbine blades is yet to be established.

3. Life cycle impact assessment methodology

3.1. Goal and scope of the study

The goal of this LCA is to determine the potential environmental benefits of energy generated by a medium capacity wind turbine (0.5–1 MW (Laurie, 2022)) equipped with OLCF reinforced epoxy composite blades. The objective of this study is twofold as summarized and shown in Table 1.

In addition, the environmental externality costs (EECs) are quantified for: (a) BIOMAT and three market incumbent turbine blade options considered for comparative assessment; and (b) electricity generated by 0.8 MW wind turbine equipped with respective blades and operates in a onshore windfarm for 20 years.

3.2. System boundary

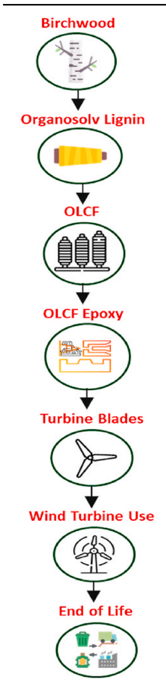
A system boundary showing the production of OLCF from organosolv lignin is shown in Fig. 2A whereas downstream life cycle stages associated with manufacturing of BIOMAT turbine blade, its use in turbine and end of life are shown in Fig. 2B respectively.

3.2.1. Production of organosolv lignin carbon fibers (OLCF)

Briefly, birch wood chips are loaded into an organosolv reactor. Then, the reactor is filled with a 70% v/v ethanol in water solution and the contents undergo fractionation at 200°C for 30 min, followed by separation of the liquid phase (containing solubilized lignin and hemicellulose) from the cellulose-rich pretreated solids via filtration. Ethanol is evaporated from liquid phase, condensed and collected in a solvent recovery unit where it undergoes purification process and is returned back to organosolv reactor system. The processing burdens of solvent recovery unit and amount of ethanol as makeup are included in the system boundary.

The resultant aqueous solution containing lignin and hemicellulose sugars is centrifuged to separate lignin into a wet paste, leaving the aqueous solution containing the hemicellulosic sugars. The lignin wet paste is then subjected to drying step to produce dried lignin powder in a pelletized form. The dried lignin pellets are extruded into lignin fibers. Finally, lignin fibers undergo stabilization and carbonization processes to obtain OLCF. The cellulose-rich solids and the extracted hemicellulose fraction are digested in an anaerobic digestion (AD) unit. The biogas produced from AD unit is combusted in a combined heat and power (CHP) motor to generate electricity and heat that will be catered to meet energy needs of lignin extraction plant.

Table 1
Objectives of the LCA study (Icons are free icons obtained from Flaticon (2024)

Life Cycle Stages	Objective of LCA Study
	1 Evaluate cradle to gate environmental footprint of OLCF produced from organosolv lignin precursor with birch biomass as raw material. The results are compared with PAN-CF produced in Sweden (CF-SE) and PAN-CF produced elsewhere in Europe (CF-RER) **Functional** Unit: 1 kg of carbon fibers. 2 Perform cradle to grave LCA study and evaluate the environmental performance of wind turbine blades fabricated from OLCF reinforced epoxy composites (from now referred as BIOMAT) and compare with existing blade variants. The market incumbent options considered for comparative assessment include: (a) GF turbine blade (GFTB); and (b) PAN-CF turbine blade (CFTB). The BIOMAT blades assumed to be manufactured in Sweden. Production of GFTB occurs elsewhere in Europe whereas for CFTB two production locations both within Sweden and in other parts of European region are considered. Thus, CFTB are differentiated as CFTB-SE (Sweden) and CFTB-RER (European average electrical grid used for production) based on their manufacturing origin. The use and end of life stages for all wind turbine blades are located in Europe. **Functional Unit: :** Three blades installed in 0.8 MW capacity wind turbine located in an onshore wind farm in Europe and has an operating lifespan of 20 years. Sweden is considered as the geographical boundary of this LCA

3.2.2. Manufacturing, use and end of life of BIOMAT turbine blade

BIOMAT blades are manufactured using resin the infusion molding (RIM) fabrication technique. First, OLCF are woven into a fabric and placed in the infusion mold. Epoxy resin is slowly (without air bubbles) infused into the mold, and the constituents are thermally cured to produce individual components of BIOMAT blades i.e., spar caps, shear web skins and blade shells (suction and pressure side). PET foams are glued with shear web skins using adhesive. The resulting shear webs are sandwich structures (OLCF epoxy core skins plus PET foam core) that act as a support for joining two blade shells. PET foams are also attached separately to suction and pressure side blade shells. These individual components of the blade are assembled using an adhesive. Finally, the blade is surface coated typically with a polyurethane (PU) based primer and topcoat layers (total thickness of 160 μm) (Teknos, 2018). The procedure is repeated and three blades suitable for installation into a 0.8 MW capacity wind turbine are manufactured. The surface coating process is excluded from this LCA study because it is a common step for BIOMAT and incumbent blades. The three-surface coated BIOMAT blades are assembled into a wind turbine which is installed on an onshore wind farm for electricity generation. The lifespan of BIOMAT wind turbine blade is assumed to be 20 years (Justine and Povl, 2016). At the conclusion of its useful life, BIOMAT blades are subjected to end-of-life management. They are dismantled from the turbine, shredded into smaller fractions and sent to incineration.

3.3. Life cycle inventory (LCI) of OLCF and BIOMAT wind turbine blade

3.3.1. Modeling assumptions

The sources of foreground data used, and assumptions made with respect to construction of LCI datasets related to BIOMAT turbine life cycle are summarized in Table 2.

The LCI modeling was done using SimaPro PhD, LCA software version 9.6.01 (Pre, 2024) and Ecoinvent (v. 3.10) (Ecoinvent, 2024) used for background LCI datasets. These datasets in Ecoinvent database are adjusted accordingly to reflect Swedish (SE) geographical conditions wherever necessary SE electrical grid mix and heat from wood chips is used for electricity and thermal energy inputs respectively in foreground LCI datasets pertaining to life cycle of BIOMAT blade.

For CFTB-RER, LCI model considers that electricity requirements for stabilization and carbonization of carbon fibers, fabrication (i.e., weaving fabric and resin infusion molding) of blade are met from European (RER) grid mix. For CFTB-SE, electricity for same operations is supplied from SE electricity grid mix. On other hand, the European region (reflecting RER dataset in Ecoinvent database) is assumed for GFTB. LCI modeling assumptions related to manufacturing of GFTB, CFTB-SE and CFTB-RER are identical to BIOMAT blades except for one difference in fiber reinforcements used (i.e., GF in GFTB, PAN CF produced with RER electrical grid mix for CFTB-RER and PAN-CF produced with SE electrical grid mix for CFTB-SE respectively).

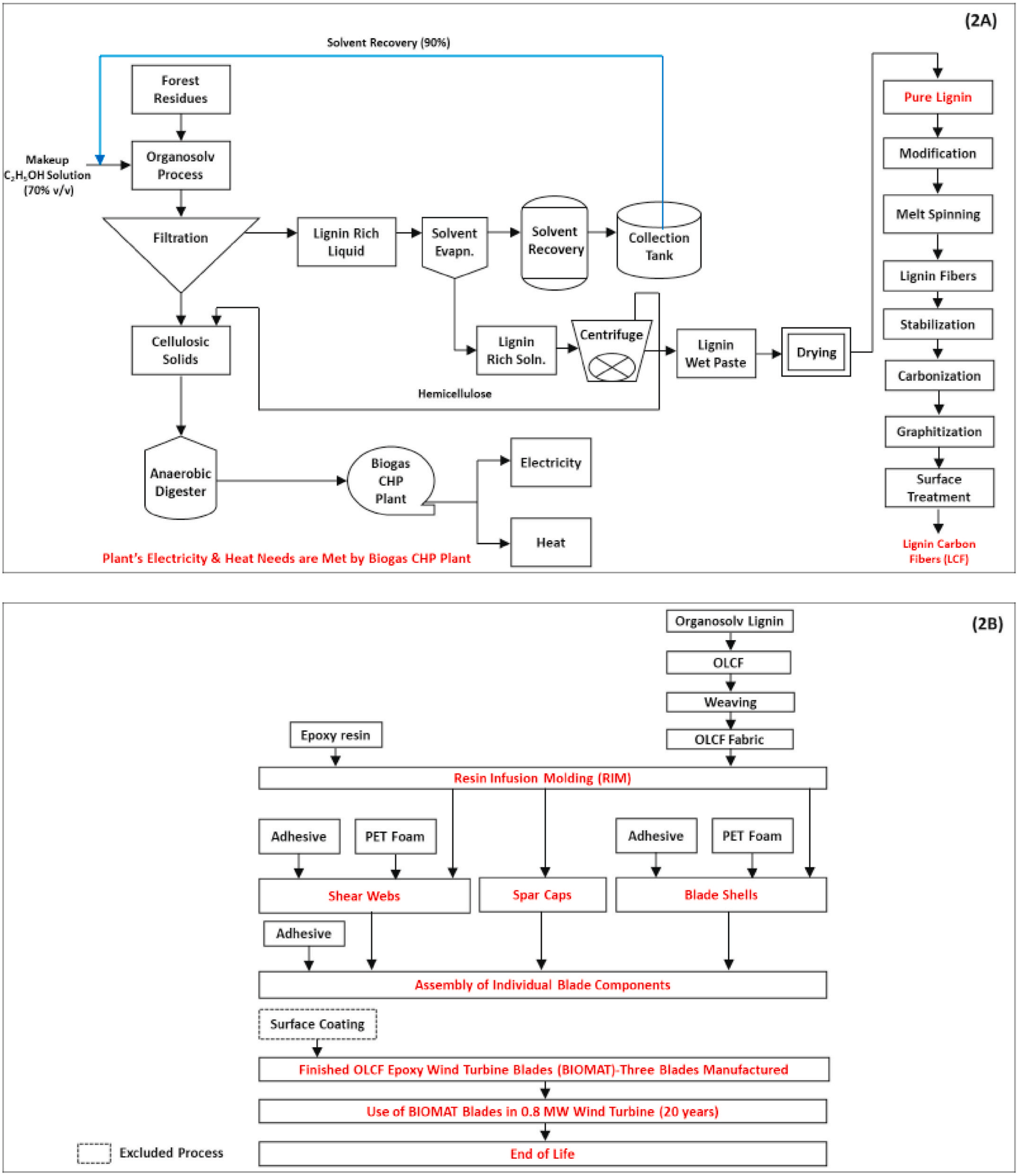


Fig. 2. (A) System boundary showing cradle to gate life cycle stages associated with an organosolv lignin based value chain; (B) System boundary showing fabrication of BIOMAT wind turbine blades, use and end of life stages.

3.3.2. Material composition of wind turbine blades

The weight and material composition of turbine blades considered in this study are shown in Table 3.

3.4. Life cycle impact assessment methodology

3.4.1. Determination of midpoint environmental impacts

The environmental burden of eleven midpoint impact assessment categories is quantified using EN15804 +A2 assessment method

Table 2
Data sources used and major assumptions considered in construction of life cycle inventory (LCI) model of BIOMAT blade.

Life Cycle Stage	Summary of data sources used and important assumptions
Production of organosolv lignin	**Production of Organosolv Lignin and OLCF** • LCI data of organosolv lignin production (developed based on our published experimental studies (Matsakas et al., 2018)) is taken from our published LCA study (Shanmugam et al., 2019). • Yield of lignin obtained from organosolv process = 12.8% w/w (with 97.5% purity) (Matsakas et al., 2018).
Production of OLCF from pure lignin	• For melt spinning of lignin fibers, processing data of viscose fiber in Ecoinvent database is used (Ecoinvent, 2024). • Stabilization and carbonization steps consume 50% and 30% lower energy than PAN based carbon fibers (Janssen et al., 2019), which is obtained from literature (Romaniw, 2013). • OLCF production yield = 50% (Chen, 2014; Souto et al., 2018).
Production of BIOMAT wind turbine blade	**BIOMAT wind turbine life cycle** • Yield of woven OLCF fabric = 89% (Witik et al., 2012). 11% scrap generated during weaving and cutting process. Fabric offcuts are incinerated with a thermal energy recovery credit is taken (Dong et al., 2015). Weaving process consumes 5.06 kWh electricity and 9.85 kJ heat per kg of OLCF. LCI for weaving obtained from Ecoinvent database (Ecoinvent, 2024). • LCI data of epoxy and PET foam was obtained from Ecoinvent database. LCI data for adhesive obtained from literature (Messmer, 2015). • 100% RIM yield assumed for all blade components. • Energy consumption of RIM is 10.2 MJ/kg. • LCI developed for RIM consumables is obtained from one of our previously published studies (Shanmugam et al., 2019).
Use stage of turbine	• Life span of wind turbine = 20 years (Justine and Povl, 2016). The preventive maintenance activities due to leading edge erosion (LEE) of turbine blades are not accounted in this study.
End of life of turbine	• Energy consumption of shredding WT blade scrap = 24 kWh/ton (Shonfield, 2008). • Incineration with energy recovery is considered as end-of-life strategy. LCI data for incineration of composite scrap obtained from literature (Dong et al., 2015).

developed under environmental products declaration EN 15804 is used (PreSustainability, 2023). The results of eleven selected midpoint impact assessment categories reported in this study include: (a) Global Warming Potential (GWP)-Total measured as kg CO_2 eq.; (b) GWP-Fossil also measured as kg CO2 eq..; (c) Ozone Depletion Potential (ODP) as kg-CFC 11 eq.; (d) Human Toxicity Cancer Potential (HH-CP) as CTU_h; (e) Human Toxicity Non Cancer Potential (HH-NCP) as CTU_h; (f) Particulate Matter Formation Potential as Disease Incidence Unit (DIU); (g) Acidification Potential (AP) as mol H^+ eq.; (h) Photochemical Ozone Formation Potential (POFP) as kg NMVOC eq.; (i) Freshwater Eutrophication Potential (FEP) as kg P eq.; and (j) Freshwater Ecotoxicity Potential (FETP) measured as CTU_e.; and (k) Fossil Depletion Potential (FDP) measured as MJ.

3.4.2. Calculation of total environmental externality costs

The total environmental impact scores of GFTB, CFTB-SE, CFTB-RER and BIOMAT blades are multiplied with unit environmental externality prices specified by the environmental prices handbook for EU region (Smith et al., 2020) to obtain EECs of respective wind turbine blades. The EEC of respective wind turbine blades is mathematically represented using equation (2).

Table 3
Bill of materials and weights of three wind turbine blades.

Material	GFTB		CFTB-SE and CFTB-RER		BIOMAT	
	kg	wt.%	kg	wt.%	kg	wt.%
PET Foam	1596	13.3	1182	13.3	1182	13.3
Adhesive	96	0.8	72	0.8	72	0.8
Epoxy resin	3138	26.15	2775	31.25	2775	31.25
Glass fibers	6462	53.85	NA	NA	NA	NA
PAN-CF	NA		4326	48.7	NA	NA
OLCF	NA		NA	NA	4326	48.7
Parasitic resin	708	5.9	525	5.9	525	5.9
Total	12000	100	8880	100	8880	100

a) Weight of one GFTB installed in 0.8 MW capacity wind turbine is 4 tons (Sanchez and Garcia, 2013). The total weight of one CFTB-SE, CFTB-RER and BIOMAT is 26.05% lighter than GFTB. This is calculated based on fiber reinforcements and epoxy resin used in fabrication of spar caps, shear webs and blade shells.
b) Material composition of blades is taken from literature (Griffith and Aswill, 2011). A parasitic resin amount of 5.9% is extra resin injection due to inefficiencies of RIM process(Griffith and Aswill, 2011).
c) The weight of spar caps is 37% of total weight of GFTB whereas it is only 15% for blades with CF reinforcement (Ennis et al., 2019).
d) GF content in spar caps and all other components of GFTB is 70 wt% and 65 wt % respectively whereas CF content in spar caps and other components of CF blades is 65 and 60 wt% (Ennis et al., 2019).

$$TEEC_{\,WTB-V} = \left[\sum\left(EI_{WTB-V} \times \frac{€}{UEEC_{WTB}}\right)\right] \tag{2}$$

Where.

$TEEC_{\,WTB-V}$ = Total EEC of individual wind turbine blade. Here V represent the variant i.e., GFTB/CFTB-SE/CFTB-RER/BIOMAT

EI_{WTB-V} = Individual environmental impact score of individual wind turbine blade variant

$\frac{€}{UEEC_{WTB}}$ = Unit environmental externality price corresponding to environmental impact score

The electricity produced by a 0.8 MW wind turbine over its 20 year lifetime is calculated using equation as per equation (3).

$$LElec_{WT} = \left[ACF \times 0.8\ MW \times 20\ yrs. \times \left(\frac{365\ days}{yr.}\right) \times \left(\frac{24\ hrs.}{day}\right)\right] \tag{3}$$

Where,

$LElec_{WT}$ = Lifetime electricity generated by a 0.8 MW wind turbine in 20 years.

ACF = Average capacity factor of wind turbine. The European ACF for onshore wind turbine = 22% (IRENA, 2019). Thus, the amount an electricity production by a 0.8 MW capacity onshore wind turbine over a lifetime of 20 years is 30,835 MWh.

The total environmental impact of energy generation by a 0.8 MW capacity wind turbine equipped with different blade options are also quantified and results are monetized to determine respective EECs. The TOTAL EEC of energy generation is mathematically represented using equation (4).

$$TEEC_{\,WT-V} = \left[\sum\left(EI_{WT-V} \times \frac{€}{UEEC_{WTB}}\right)\right] \tag{4}$$

Where,

$TEEC_{WT-V}$ = Total EEC of wind energy generated by 0.8 MW turbine over its 20 year lifetime.

V represents wind turbine equipped with different blade type (GFTB/CFTB- SE/CFTB-RER/BIOMAT).

EI_{WT-V} = Individual environmental impact score of lifetime energy generated by a 0.8 MW wind turbine equipped with a particular blade variant.

$\frac{€}{EE_{WT}}$ = Unit environmental externality cost corresponding to an environmental impact score

The environmental benefits to investment ratio (EBIR) of replacing incumbent blade options with BIOMAT is calculated using equation (5).

$$EBIR = \left[\frac{TEEC_{WT-V} - TEEC_{WT-BIOMAT}}{TEEC_{BIOMAT\ Blades}}\right] \quad (5)$$

Where,

$TEEC_{WT-BIOMAT}$ = Total environmental externality costs of lifetime energy generated by wind turbine equipped with BIOMAT blades

3.5. Alternate scenario analysis

A scenario analysis is conducted by replacing conventional fossil-based epoxy resin with organosolv (i.e., bio-based) lignin epoxy as a polymer used for fiber reinforcement. In baseline LCI model, 3300 kgs (2775 kgs for reinforcement + 525 kg parasitic resin due to inefficiencies of RIM process (refer to Table 3) for CFTB-RER, CFTB-SE and BIOMAT variants, and 3846 kgs (3138 kgs for reinforcement + 708 kgs parasitic) of fossil (bisphenol-A) based epoxy resin is inventoried as a polymer matrix for manufacturing wind turbine blades. In alternate scenario analysis, the same amount of resin is replaced with biobased epoxy produced from organosolv lignin and epoxidized soybean oil. The LCI data for production of lignin epoxy resin is obtained from one of our previously published articles (Shanmugam et al., 2019).

3.6. Uncertainty analysis

Lifecycle environmental performance of BIOMAT blades is subjected to variations when governing LCI model parameters such as weight of OLCF reinforcement, lifespan of BIOMAT blades, and OLCF yield, etc., are changed. Thus, an uncertainty analysis is performed by varying critical LCI modeling parameters associated with lifecycle of BIOMAT blades. Key parameters varied, and their description is summarized in Table 4. As explained in the table, the proposed change in LCI modeling parameters depict a worst-case scenario of BIOMAT blades. An advantage is intentionally given to the incumbent blades options to compare the environmental performance of BIOMAT blades with best case market incumbent counterparts. This is because, BIOMAT is a hypothetical product under nascent developmental stage and yet to completely prove its technical competency.

For incumbent blade variants, the energy consumption variation of weaving fibers, RIM process and shredding blades at end of life is similar to BIOMAT blades. Uncertainty analysis was performed by Monte Carlo simulations in Simapro (Pre, 2024) with 5000 steps and 95% confidence level.

Table 4
Modeling parameters of BIOMAT blade changed for uncertainty analysis.

Parameter Varied	Description
Energy consumption incurred for stabilization and carbonization steps of OLCF production	• Energy consumption of stabilization and carbonization varied from 0.5 to 1 times and 0.3 to 0.6 times energy needed for respective steps in production of PAN-CF. Energy consumption for stabilization & carbonization of LCF is 50% and 30% less than PAN-CF (Janssen et al., 2019). So, considering same energy consumption equal to PAN-CF is the worst-case scenario
OLCF production yield	• LCF Yield varied from 45 to 50% as specified in literature (Chen, 2014; Souto et al., 2018).
OLCF reinforcement in BIOMAT blades	• OLCF content of the blade varied from 65% to 70% in spar caps and 60–65% in shear webs and blade shells.
Manufacturing BIOMAT blades	• Energy consumption of: (a) weaving OLCF fabric varied from 2.1 to 5.06 KWh/kg (Ecoinvent, 2024; Koc and Clincik, 2010), and RIM process from 0.70 to 2.83 KWh/kg (Song et al., 2009).
Lifespan of BIOMAT blades	• BIOMAT blades lifespan varied from 20 to 15 years. Thus, weight of one incumbent (GFTB/CFTB-SE/CFTB-RER) blade = 1.33 times weight of BIOMAT blade to match functional unit equivalency. Thus, weights of OLCF and epoxy resin varied from 4860.67 to a maximum of 6479.27 kg and from 3300 to 4389 kgs respectively. Correspondingly weaving of OLCF also varied from 4860.67 to 6479.27 kg and amount subjected to RIM process varied from 8880 to 11810.4 kg
End of life of BIOMAT blades	• Energy consumption for shredding blades at end of life varied from 16 to 30 KWh/ton(Shonfield, 2008).

4. Results and discussion

4.1. Environmental footprint of OLCF

The cradle to gate environmental impact assessment results of OLCF in comparison with PAN-SE and PAN-RER is shown in Fig. 3.

OLCF outperforms PAN-CF-RER in all eleven impact assessment categories quantified. The GWP-T impact of OLCF has a negative score because uptake of biogenic carbon is greater than greenhouse gas (GHG) emissions released. The GHG burden arising from production of OLCF is completely offset by biogenic carbon uptake from feedstock material (i.e., wood chips). Thus, the production of OLCF from wood chips can be claimed as carbon neutral but only when intensive sustainable forest management practices are followed i.e., depreciation of forest cover is less than its replenishment (Eggers and Schulte, 2023). The GWP-F impact of OLCF is 78% lower than PAN-CF-RER and this is mainly attributed to two factors: (a) optimized electricity consumption of organosolv process where we considered biogas generated from digestion of cellulosic and hemicellulosic solids is combusted in a combined heat and power unit and meet energy needs of the plant; (b) energy consumption during stabilization and carbonization steps of lignin based CF is 50% and 30% lower than CF from PAN precursor respectively (Janssen et al., 2019). Among other impact categories, OLCF performs environmentally better by 85–94% in PMFP, FEP, ODP, FETP, HH-NCP and AP impact categories, by 71% in FDP, 63% in POFP, and 25% in HH-CP categories respectively when compared with PAN-CF-RER. The environmental performance of OLCF is also better than PAN-CF-SE in nine out of eleven impact categories. The burden of OLCF is 43–90% lower than the PAN based carbon fiber produced in Sweden (PAN-CF-SE) in FDP, ODP, FETP, HH-NCP, AP, and PMFP impact categories. On the other hand, OLCF imposes a higher burden in FEP (by 10%) and HH-CP (by 26%) than PAN-CF-SE. OLCF has a higher impact in these categories. High HH-CP is largely attributed to consumption of ethanol solvent (as makeup) which is a known carcinogen (Bevan et al., 2009).

PAN-CF-SE also exhibits improved environmental performance compared to PAN-CF-RER. The environmental impact reduction of PAN-CF-SE by 34–97% in nine of eleven impact categories reiterates the strategic importance of locating carbon fiber production plants in Sweden where the benefits of low carbon electrical grids can be realized. Poor environmental performance of PAN-CF-RER is anticipated because higher impacts are attributed to the electricity used for thermal stabilization and carbonization of carbon fibers. The electricity production with RER grid mix includes 43% of the share from fossil sources (coal, oil and natural gas combined) which is responsible for higher environmental impacts. Current carbon intensity of European average grid (RER) mix is 324g CO_2/KWh electricity (Ecoinvent, 2024). Germany and France being major carbon fiber producing countries in Europe

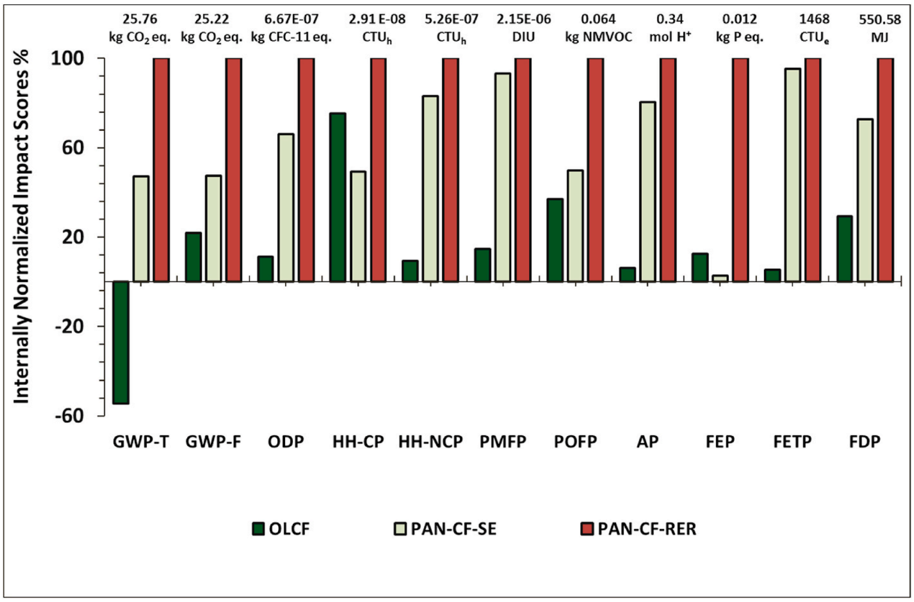


Fig. 3. Cradle to gate environmental impacts of manufacturing 1 kg of organosolv lignin carbon fibers (OLCF), PAN based CF produced with SE and RER electricity grid mixes.

(S&PGlobal, 2022). The actual environmental footprint of PAN-CF can be much higher if produced in Germany (carbon intensity of 418g CO_2/KWh (Ecoinvent, 2024)) or at least greater than Sweden if produced in France (carbon intensity of 77g CO_2/KWh (Ecoinvent, 2024)).

4.2. Life cycle environmental performance of wind turbine blades

4.2.1. Contribution analysis of BIOMAT wind turbine blade

The contribution analysis results of BIOMAT blades are shown in Fig. 4.

The results of contribution analysis suggest that consumption of OLCF and epoxy resin is responsible for 75–87% of total burden in all categories except for climate change and ozone depletion. The GWP-F contributes to 65% of the total impact but biogenic carbon update from using wood chips as feedstock during OLCF production completely negates the climate change burden. Use of epoxy resin as a polymer matrix in fabrication of BIOMAT blades alone generates 25–69% of the impact in ten out of eleven impact categories (except ODP) with highest contribution of 52–69% made towards human toxicity (carcinogenic) and freshwater ecotoxicity potential. A scenario analysis is therefore conducted to the extent of reduction of environmental burden when conventional epoxy resin is replaced with biobased organosolv lignin epoxy resin. The ODP impact is driven by Resin Infusion Molding (RIM) process (92% of the total impact) and attributed to polytetrafluoroethylene coated glass fabric which is used as mold consumables. The end-of-life stage has negligible (less than 2% = contribution in all impact categories). Energy recovery credits from incineration of OLCF-epoxy composite (contain 31 MJ/kg energy content (Dong et al., 2015)) and assumed 85% energy recovered with 33% electricity and 67% heat credits respectively (Ecoinvent, 2024)). This overall environmental burden of OLCF epoxy composite blades by 6–51% in seven impact categories with a significant reduction of 51% seen in AP, 32% in PMFP,

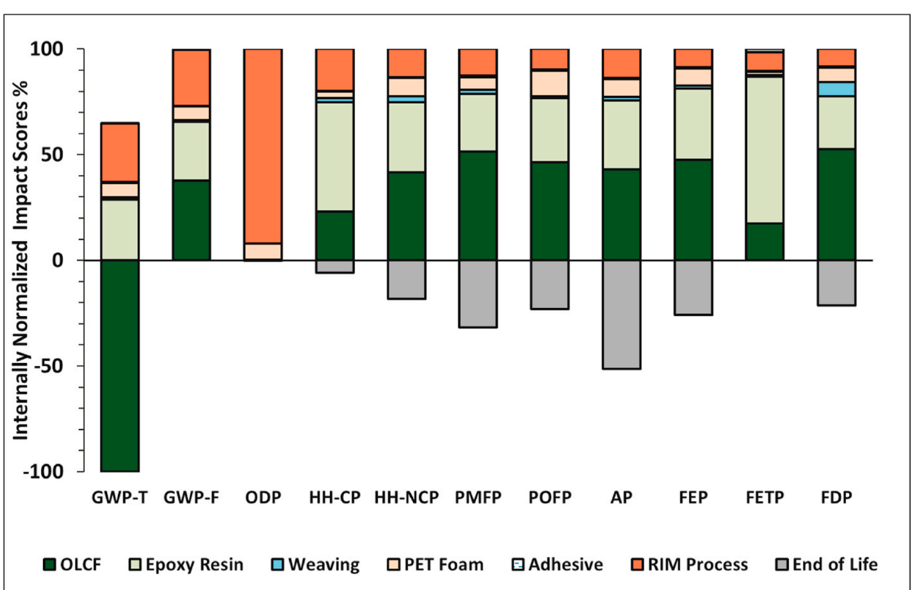


Fig. 4. Contribution analysis of BIOMAT blades.

26% FEP, followed by 18–23% reduction in FDP, HH-NCP and POFP impact categories.

4.2.2. Comparing impacts of BIOMAT blade with market incumbent options (baseline and alternate scenario results)

The life cycle environmental performance of BIOMAT turbine blade in comparison with: (a) CFTB-SE; (b) CFTB-RER; and (c) GFTB for baseline and alternate scenario are shown in Fig. 5.

BIOMAT blades are carbon negative (seen from negative GWP impact scores in Fig. 5A) compared to incumbent counterparts in both, baseline and alternate scenarios evaluated. This is attributed to birchwood, a biogenic feedstock used in production of BIOMAT blades. Also, the GWP-F (i.e., quantifying only fossil GWP) of BIOMAT blades is 29% (result not shown) lower than GFTB, 31% and 59% lower than CFTB-SE and CFTB-RER blades respectively. This clearly suggests climate friendliness of BIOMAT blades even without accounting negative GWP score due to biogenic carbon sink contributed by birchwood feedstock. The use of biobased lignin epoxy resin as polymer matrix (alternate scenario analysis) is more beneficial because GWP-T of BIOMAT blade exhibit a greater carbon sink possibility (−43 tons Vs −24 tons) whereas the impact of CFTB-RER, CFTB-SE and GFTB is 6%, 10% and 12% than their respective baseline (i.e., with use of fossil epoxy resin as polymer matrix) scores. The GWP-F (result not shown) of BIOMAT blades is 32% lower than GFTB, 34% and 52% lower than CFTB-SE and CFTB-RER respectively.

The ODP (Fig. 5B) of four blade types is almost similar and no significant difference observed in the scores of both baseline and alternate scenarios. The HH-NCP and AP (Fig. 5D and G) of BIOMAT blades is lower by 67–93% lower than all existing blade options. The environmental burden of BIOMAT is 75–82% lower than CFTB-SE and CFTB-RER blades, and 8–29% lower than GFTB blade in PMFP and FETP (Fig. 5E and I) impact categories. For CFTB-RER and CFTB-SE variants, these impacts are caused by blade manufacturing stage and particularly attributed to ammonia and hydrogen cyanide (HCN) emissions released during production of PAN-CF which is the cause of major environmental concern (AZOMaterials, 2014; Hajalifard et al., 2014). HCN is highly toxic to both, humans and other aquatic species(Barber et al., 2003) (it disrupt oxygen metabolism) and therefore responsible for high HH-NCP and FETP impacts. On the other hand, release of ammonia contributes to secondary production of aerosols (Duan et al., 2021) and increases atmospheric acidification (ApSimon et al., 1987) causes high PMFP and AP impacts. The HH-NCP and AP of GFTB are high and largely driven by use of glass fibers and epoxy resin.

The outcome of HH-CP, POFP, FEP and FDP impact categories is interesting because a noticeable variation is observed between the results of baseline and alternate scenario analysis. From Fig. 5C, it is evident that all four blade variants have similar profile for HH-CP impact category. The HH-CP impact of BIOMAT blades is only 8% higher than CFTB-SE and only marginally lower (4–9%) than CFTB-RER and GFTB variants. By replacing the fossil based epoxy resin with its biobased (lignin epoxy) counterpart, BIOMAT blades perform 16% better than CFTB-RER but the impact is 6–16% higher than CFTB-SE and GFTB blade types. However, an intra comparison between variants i.e., comparing baseline with alternate scenario of the same blades, HH-CP of the latter is 43–52% lower for all four variants. This reduction in alternate scenario is due to replacement of cancer causing bisphenol-A based epoxy resin (Gao et al., 2015) with a biobased equivalent (lignin epoxy) as a polymer matrix for manufacturing wind turbine blades. The POFP impact (Fig. 5F) of BIOMAT blades are 17–52%, and 20–57% lower than incumbent blade variants for baseline and alternate scenarios respectively. The FDP (Fig. 5J) of BIOMAT is 50–63% and 56–68% lower compared to baseline and alternate scenario results of CFTB-SE and CFTB-RER but is marginally higher than GFTB. These impacts are caused by combination of two factors namely manufacturing electricity consumption and use of epoxy resin as a polymer matrix for fabrication of turbine blades. Electricity for production of CFTB-RER and GFTB is modelled using European energy mix (RER). Around 13.5% of this energy mix generated by coal (IEA, 2024) which is responsible for high POFP and FDP impacts (EIA, 2024). On the other hand, use of epoxy resin also contributes to smog formation (due to release of volatile organic compounds and fossil depletion impacts. All four wind turbine blade variants using lignin epoxy resin as a polymer matrix (alternate scenario) perform better than their fossil counterparts (baseline) by 13–30% and 8–25% in POFP and FDP impact categories respectively.

The FEP impact of BIOMAT blade for baseline is 69% and 84% lower than CFTB-RER and GFTB variants, whereas it is lower by 31–41% for alternate scenario. However, BIOMAT has higher FEP impact than CFTB-SE. Increase in freshwater eutrophication is probably one of the significant tradeoffs of using biobased (lignin epoxy) resin for manufacturing wind turbine blades. This is evident from 51 to 92% increase in impact of all blade types in alternate scenario (due to use of lignin epoxy resin) when compared with their respective baseline variants.

4.2.3. Uncertainty analysis

The uncertainty analysis results of BIOMAT and incumbent blade variants is shown in Fig. 6.

The results of uncertainty analysis reveal that climate change (GWP-T) and acidification (AP) impacts of BIOMAT blade will always be lower (beyond ambiguity) than all three market incumbent blade variants. Also, for given uncertainties introduced (Table 4), the performance of BIOMAT is always better than CFTB-SE and CFTB-RER blade variants in PMFP and FETP impact categories. However, a significant overlap is observed between scores of BIOMAT and GFTB in these categories. The difference in FETP impact of BIOMAT and GFTB from baseline LCA (Fig. 5I) is only 8–9% but it is 29% for PMFP in favour of BIOMAT blades (i.e., they perform better than GFTB). This is mainly due to reduced lifespan of BIOMAT blades from 20 to 15 (weight of 1 GFTB = 1.33* weight of BIOMAT blade to match the functional unit of 20 years) years requiring greater amounts of raw materials (mainly OLCF and epoxy) can increase PMFP impact which can result in loosing advantage over GFTB. The ODP has no meaningful interpretation because the impact scores are identical for all blade variants. The POFP and FDP impacts of BIOMAT blades always perform better than CFTB-RER but overlapping scores are seen when compared with CFTB-SE and GFTB. The difference in FDP impact of BIOMAT and GFTB variants is only 4% in favour of GFTB but for POFP impact category the difference is 30%. Thus, the environmental advantage of BIOMAT blades will be waned off with increase in electricity consumption attributed to additional requirement of raw materials and processing (e.g., weaving, infusion curing etc) steps if their service life is reduced from 20 to 15 years. Finally, the FEP impact of BIOMAT blades expected to perform better than CFTB-RER and GFTB blades although the latter two exhibit large fluctuations in impact scores. This is caused by variation in electricity consumption during fiber weaving and RIM processing steps which is drawn from 13.5% coal based EU energy mix responsible for eutrophication (Gaete-Morales et al., 2019). But CFTB-SE always expected to be lower than BIOMAT blade (although a minor overlap) because of low carbon intensive SE electrical grid mix.

4.2.4. Results of environmental externality costs

The total EECs of BIOMAT and incumbent blade variants is calculated using equation (2) and results shown in Fig. 7.

The total EEC of BIOMAT blades is 74–88% lower than the existing GF and PAN-CF incorporated wind turbine blades. Environmental externality costs attributed to GWP-T impact (i.e., the damage costs resulting from climate change) alone accounts for 45–68% of the total EEC incurred by incumbent blades. On the other hand, BIOMAT blades are carbon negative (−24 tons) because they use OLCF as a strength bearing reinforcement which is produced from a biogenic birchwood feedstock. However, for EEC calculation, we considered GWP-T of BIOMAT blade as zero (and no EEC credit given although its GWP-T value is −24 tons). Also, the climate change EEC of BIOMAT blades

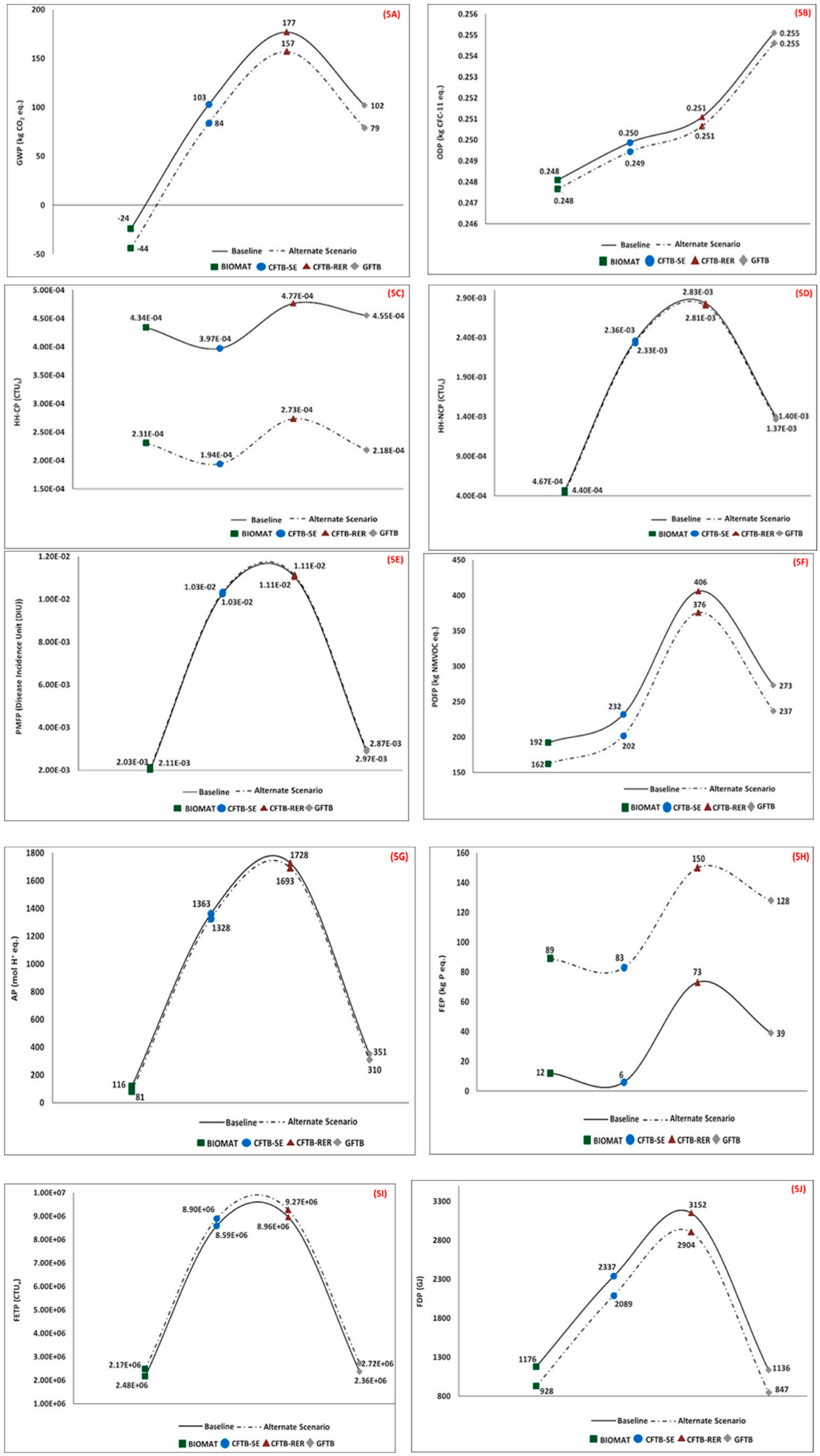


Fig. 5. Comparison of midpoint environmental assessment impact results of BIOMAT, CFTB-SE, CFTB-RER and GFTB of baseline and alternate scenarios.

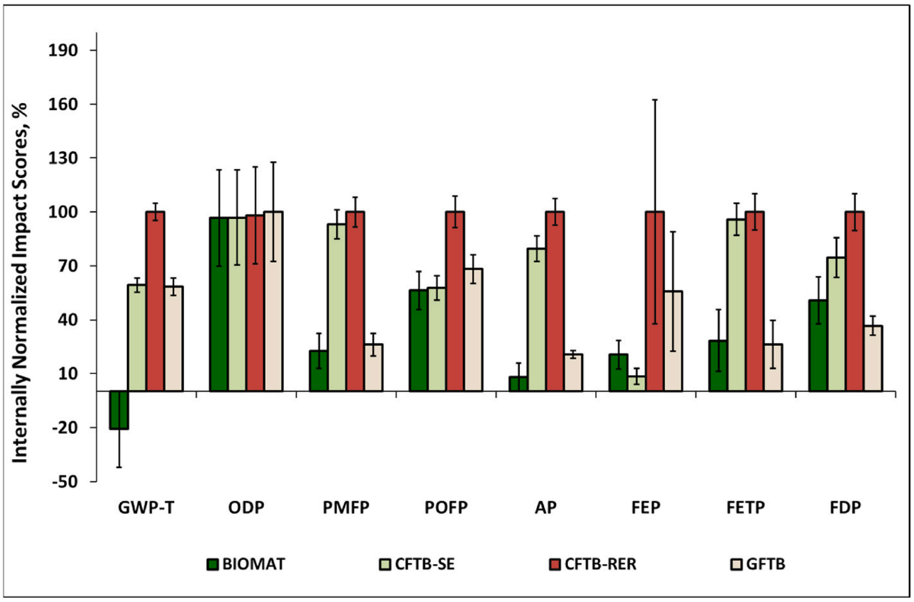


Fig. 6. Uncertainty analysis of BIOMAT, CFTB-SE. CFTB-RER and GFTB blade variants (uncertainties of HH-CP and HH-NCP are not showing because background data uncertainty is too high and makes it statistically inconclusive).

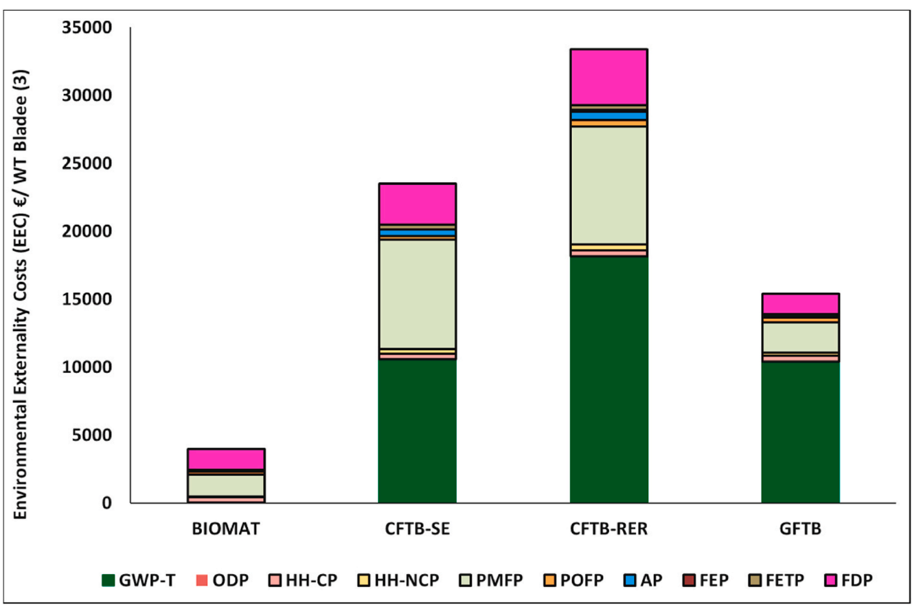


Fig. 7. Total EEC BIOMAT, CFTB-SE, CFTB-RER and GFTB wind turbine blade variants (Total EEC calculate for three blades used in one 0.8 MW wind turbine).

are 30–59% lower than the incumbent blade variants even if only global warming potential-fossil impact (GWP-F) is considered (GWP-F EEC is not included in Fig. 7). The individual EEC contribution of PMFP and FDP impacts towards total EEC is also high for all blade variants including BIOMAT. In fact, the potential damage caused by these two impacts amounts to 70% of the total EEC of BIOMAT blade. The contribution from PMFP and FDP lies between 24 and 47% of the total EEC generated by incumbent blades.

The $TEEC_{WT-V}$ and *EBIR* of an onshore 0.8 MW wind turbine unit operating for 20 years and equipped with respective blade variants is calculated using equations (4) and (5) respectively and results are summarized and shown in Table 5.

The $TEEC_{WT-V}$ is lowest for wind turbines equipped with BIOMAT blades and ascends in the order of BIOMAT > GFTB > CFTB-SE > CFTB-RER. The total environmental damage cost incurred by wind turbine with BIOMAT blades is 11% lower than turbine with GFTB, 17 and 23% respectively lower than wind turbines with CFTB-SE and CFTB-RER

Table 5
Total environmental externality costs of different blade options, lifetime electricity generated by wind turbine using respective blade variants and corresponding EBIR.

Blade Type	$TEEC_{WTB-V}$ (€)	T EEC_{WT-V} (€)	EBIR
BIOMAT	3970	116334	
CFTB-SE	23502	140192	6.01
CFTB-RER	33371	150891	8.70
GFTB	15386	131395	3.79

variants. The EBIR of wind energy generation replacing GFTB, CFTB-SE and CFTB-RER with BIOMAT blades is 3.79, 6.01 and 8.70 respectively. EBIR is the ratio of reduction in environmental externality costs of energy generation by 0.8 MW capacity wind turbine when respective incumbent variants are replaced with BIOMAT blades. Here, the total EEC of BIOMAT blades is considered as an investment whereas savings in total EEC are benefits realized from replacement of incumbent with BIOMAT blades is the benefits for wind energy generation. The positive EBIR ratio numbers indicate a clear environmental advantage of using OLCF for fabrication of wind turbine blades if their structural performance is enhanced in the near future. Detailed calculations of $TEEC_{WTB-V}$ of all blade variants, $TEEC_{WT-V}$ of wind energy generated by 0.8 MW capacity turbine and corresponding EBIR are shown in the supporting information file.

5. Conclusions

The conclusions drawn from this study are summarized as follows.

1) The overall environmental performance of OLCF is much better than PAN CF produced in Europe (other than Sweden) with RER electrical grid mix. The performance of PAN-CF improves significantly when manufactured in Sweden, i.e., using SE national grid mix. Yet its impacts are higher than OLCF in most categories. Specifically, the climate change impact from fossil carbon (GWP-F) of OLCF is 52% and 26% lower than PAN-CF-RER and PAN-CF-SE respectively. The fossil carbon is completely offset if biogenic uptake is taken into consideration. But this result must be treated with great caution and is meaningful only when intensive sustainable forest management practices are in place.
2) The overall environmental performance of BIOMAT blades is better than incumbent GFTB, CFTB-SE and CFTB-RER variants. Superior performance of BIOMAT blades is due to combination of factors including: (a) production of OLCF from a biogenic source (wood chips); (b) weight reduction by 26% when compared to GFTB; and (c) advantage of low carbon intense electricity grid owing to manufacturing of BIOMAT blades in Sweden.
3) Uncertainty analysis proved beyond ambiguity that the climate change impact (GWP) of BIOMAT blades is always lower than GFTB. CFTB-SE, and CFTB-RER variants despite reducing their lifespan reduced from 20 to 15 years (implying more weight of OLCF and epoxy materials) and increasing energy consumption of carbonization and stabilization during OLCF production. However, a major compromise of using lignin epoxy resin in increase in FEP impact which is solely driven by using epoxidized soybean oil as raw material for its production.
4) The total EEC of BIOMAT blades and corresponding energy generation by a turbine with their possession is lowest of all the blade variants evaluated in this work. Furthermore, the positive EBIR of BIOMAT blades in comparison with three incumbent options is a motivation for transitioning to use of OLCF by wind industry for manufacturing of turbine blades.

We are aware of the fact that currently OLCF is not used in structural applications such as wind turbine blades because of its inferior mechanical properties when compared to CF obtained from PAN precursor. However, owing to recent developments (as explained in section 2), the technical feasibility of producing structurally competing OLCF from hardwood biomass feedstock like birchwood is sucessfully demonstrated (Bai et al., 2024; Luo et al., 2024). Although there are several hurdles to overcome, the of OLCF into a wind industry may not be a remote possibility. Thus, a detailed study understanding environmental feasibility of using OLCF for manufacturing wind turbine blades is performed and we believe the results presented in this paper will provide early insights to key stakeholders across the value chain. Finally, from a geographical location perspective, Sweden has a strategic advantage for OLCF production because of two reasons: (a) availability of abundant biomass (especially birchwood) feedstock that eases scale-up challenges; and (b) a climate friendly downstream value chain can be established by taking advantage of low carbon intense electrical grid mix of Sweden.

CRediT authorship contribution statement

Venkata K.K. Upadhyayula: Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Dalia M.M. Yacout:** Writing – review & editing, Methodology, Conceptualization. **Kenneth G. Latham:** Writing – review & editing. **Stina Jansson:** Writing – review & editing, Project administration, Funding acquisition. **Ulrika Rova:** Writing – review & editing, Funding acquisition. **Paul Christakopoulos:** Writing – review & editing. **Leonidas Matsakas:** Writing – review & editing, Validation, Investigation, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Kenneth G Latham reports financial support was provided by Umeå University. Stina Jansson reports financial support was provided by Umeå University. Leonidas Matsakas reports financial support was provided by Lulea University of Technology. Ulrika Rova reports financial support was provided by Lulea University of Technology. Paul Christakopoulos reports financial support was provided by Lulea University of Technology. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2025.144825.

Data availability

No data was used for the research described in the article.

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