Cleaner Production Letters 10 (2026) 100137

Contents lists available at ScienceDirect

Cleaner Production Letters

journal homepage: www.journals.elsevier.com/cleaner-production-letters

Identifying materials in tidal energy technology and their effects to human health, ecosystems, and resources: A life cycle assessment perspective

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ABSTRACT

Tidal energy is an abundant and predictable renewable energy source that represents a promising alternative for reducing greenhouse gas (GHG) emissions. To promote the sustainable development of tidal energy technologies (TETs), Life Cycle Assessment (LCA) is a key method for evaluating the environmental impacts associated with materials and technological processes. Although LCA has been widely applied to other renewable technologies, available data for TETs remain limited and scarce. This research conducts a systematic review (PRISMA protocol) and data mining of LCA studies using the ReCiPe method to identify the main impacts generated by TETs and their materials. The results show significant variability among technologies, with tidal stream turbines exhibiting the highest GHG emissions (69.97 g CO_2/kWh) and bulb turbines the lowest (3.9 g CO_2/kWh). Copper affects all LCA categories with the highest negative impacts, followed by steel, which is the most widely used material in turbine manufacturing. Therefore, further research on alternative materials is necessary to replace copper and steel or to reduce their primary use in turbine manufacturing. An apparent positive trend since 2015 was observed in the reported GHG emissions of real hydrokinetic turbine LCA projects; this trend is likely influenced by data gaps in LCA databases and by differences in LCA methodologies. Hence, this research calls on academia to unify LCA methodologies and enhance databases to provide more precise and detailed information on the impacts of traditional and emerging materials used in TETs.

1. Introduction

Tidal energy is a renewable source that can be used as an alternative to reduce dependence on fossil fuels, which are the main sources of greenhouse gases (GHG). Several authors have reported that tidal energy not only has the capacity to provide electricity for the world's energy demand (Rashedi et al., 2022a; Walker and Thies, 2022), but it is also predictable because its dynamics are governed by the gravitational effects of the Moon and the Sun.

The amount of worldwide energy is considerable, according to the latest report of the International Energy Renewable Agency (IRENA) in collaboration with Ocean Energy Europe (Renewable Energy Agency, 2023) reported 10.6 MW of tidal Stream Energy deployment, and 1200 TWh of global ocean energy potential. That enormous amount of energy can be exploited with turbines capable of operating in the marine environment. Hydrokinetic turbines or stream turbines are classified into four groups i.e horizontal axis, vertical axis, oscillating hydrofoil, and venturi effect turbines, where the horizontal axis turbines are the most studied and developed for marine applications (Uihlein, 2016).

Research and technological development of stream turbines started in the United Kingdom with marine applications in 1970 (House of Commons UK, 2001). Initiatives for river applications began at the same time as tidal turbines, but river hydrokinetic turbines received fewer economic resources for development (Khan et al., 2009). However, the Technological Readiness Level (TRL) and Manufacturing Readiness Level (MRL) of the river turbines reached the commercialization stage earlier than those of the marine turbines. The hydrokinetic turbines for marine applications handle higher energy densities (MW) for electricity production than river turbines (kW), and they must withstand harsher conditions due to seawater corrosion and wind-wave-current loads. This explains why the marine turbines are still under development.

The first prototype of a tidal stream turbine, a marine hydrokinetic turbine, was deployed in 1994 in Loch Linnhe (Scotland), producing 1.5 kW (Fraenkel, 2010), and the first prototype of hydrokinetic turbines in rivers was deployed in Ruby (Alaska) in 2008 (Johnson and Pride, 2010). Despite the first prototype of stream turbines for river operation starting 14 years later than the marine counterpart, the TRL and MRL of the river turbines progressed and matured faster, while the marine stream turbines such as the O2 tidal turbine (Gillespie and Macaulay, 2019; Orbital Marine, 2025) are now in operational demonstration

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https://doi.org/10.1016/j.clpl.2026.100137
Received 19 November 2025; Received in revised form 2 March 2026; Accepted 3 March 2026

(pre-commercialization stage).

The development of tidal stream technology is in progress, and 10 turbine designs are at the highest TRL9, indicating a pre-commercial stage. However, the MRL is 2, where several companies are improving their capabilities in manufacturing, therefore the supply chain needs to be prepared for a full rate production i.e MRL 10 (TAPECON, 2025). Because the commercial production of tidal stream technology is not mature, more research is needed to identify the negative impacts of its materials, mainly those utilized in critical components like turbine blades (Walker and Thies, 2022). Considering that the TRL and MRL of hydrokinetic tidal turbines (stream turbines) have not reached the marketable stage, it is comprehensible that the studies related to the impact of the used materials on human health, natural environment (ecosystems) and resources are scarce.

LCA studies are an alternative to identify the environmental impacts of the materials used in tidal technology. However, Paredes et al. (2019a) reported only 5 LCA studies applied in tidal energy until 2019, i.e the projects of Swansea Bay Tidal Lagoon, Deep Green Tidal, Tidal Severn barrage, Seagen Marine current turbine, Deep Green Tidal (Minesto) and four turbine models: Tidal Generation Ltd. (TGL), Open Hydro, ScotRenewables, and Flumill. Then, the LCA studies applied to river stream turbines must be considered as a reference to identify the needs and gaps in performing new LCA studies on hydrokinetic turbines under more corrosive and hostile environmental conditions like marine. In this line, the progress of the TRL and MRL in tidal turbines might consider lessons from now-commercialized river turbines, avoiding errors and preventing negative impacts associated with the use of materials in river technology.

To promote the development of tidal energy technologies with environmental sustainability, the impacts of the materials used must be identified. According to this, this research performs data mining across technical reports, and scientific articles to extract relevant information on the impacts of using materials in the manufacturing, installation, operation, maintenance, and decommissioning stages of hydrokinetic marine turbines. The results of this research are organized as follows: 1-Greenhouse gas emissions from tidal energy technology, 2-Most used materials in tidal energy, and 3- Material impacts in other marine technologies.

2. Methodological approach

This research conducted a data mining and systematic literature review focused on Life Cycle Assessment (LCA) applications in the tidal energy sector. The systematic literature review goes further than a traditional literature review, because it integrates data mining to generate new scientific information, i.e, image processing and data extraction of reported data in figures of the revised literature, through ChatGPT (Open AI, 2025) and MATLAB image processing toolbox (MATLAB, 2025). The review process followed the PRISMA protocol (Fig. 1) for systematic reviews (Moher et al., 2010) a structured approach integrating the three distinct stages recommended in recent studies (Rueda-Bayona et al., 2022a; Seeger et al., 2022) i.e., input, processing and output.

2.1. Input stage

The input is the first stage of the systematic literature review, where the design of the search strategy is conducted. The strategy was set considering the keywords related to the problem i.e., tidal energy, LCA, GHG, Hydrokinetic turbines, and materials. This was followed by considering possible combinations of the keywords using the connectors AND, OR, WITH, IN. Next, relevant scientific databases were used, such

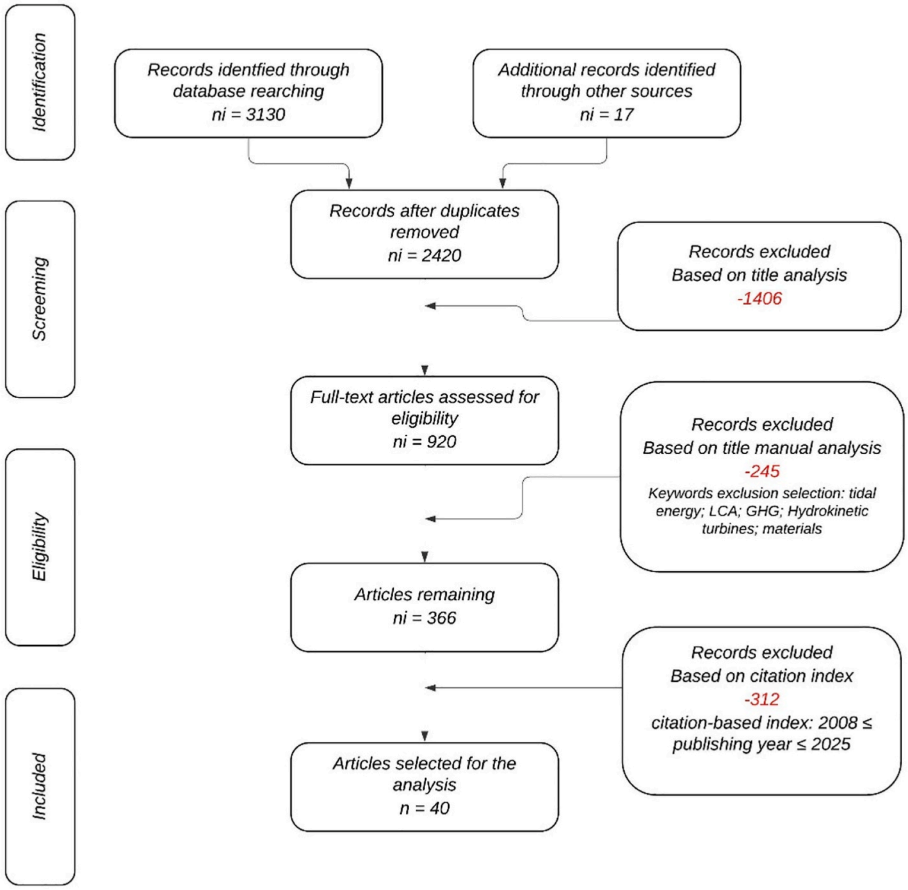

Fig. 1. Systematic research based on PRISMA protocol.

as Scopus, Web of Science, Science Direct, IEEE, ASCE, Sage, Willey, Scielo, including international repositories of Universities and Institutions. The search period was 20 years, from 2008 to 2025.

This study conducted a manual search in the above-mentioned databases, and the search was complemented using artificial intelligence through ChatGPT (Open AI, 2025) and Deep Seek (DeepSeek, 2025). False results were identified during the AI searches, as the tables generated by ChatGPT and DeepSeek listed non-existent research articles. As a result, a verification and validation process for the applied methodology was performed in the processing stage. As a good practice,

Table 1

Conducted studies in tidal turbines reporting GEI intensity. *Denotes that both studies reported identical GEI emissions.

Technology name	Year of deployment	Turbine technical details	Study	Methods/Boundary	GEI emissions
Atir tidal platform.	2019	45 m ship length, with 2 horizontal axis 3-bladed turbines, rotor with 21 diameters. 1.5 MW rated power at 1.5 m/s of current velocity.	Bianchi et al. (2024a)	Theoretical. Recipe Method, Simapro V.9.2.0.1 software/Manufacturing only (cradle-to-gate).	42.11 g CO_2/kWh
Deep Green.	2018	5-bladed horizontal Kite, turbines. 12 MW array of 24 prototypes. Rotor with 1.5 m diameter, 0.5 MW of individual rated power at 1.2-2.4 m/s	Kaddoura et al. (2020)	Theoretical. Recipe Method, openLCA software/Emissions due to the production, maintenance and operation.	26.3 g CO_2/kWh
HS1000.	2018	3-bladed horizontal-axis tidal turbine. Bottom mounted. Rotor with 21 mi of diameter, 1 MW of rated power at 2.7 m/s (Gu et al., 2024)	Douziech et al. (2016)	Real. Recipe Method. ARDA software with ecoinvent database 2.2./Life cycle – construction dominant.	37 g CO_2/kWh
Seagen. 2	2016	2-bladed turbine. Twin axial-flow rotors with 16 m of diameter, 1.2 MW of rated power (0.6 MW each rotor) at 1 m/s.	Douziech et al. (2016)	Real. Recipe Method. ARDA software with ecoinvent database 2.2./Life cycle – construction dominant.	25.5 g CO_2/kWh
Hydra Tidal.	2016	2-bladed turbine. Twin axial-flow rotors with 23 m of diameter, 1.5 MW of rated power (0.6 MW each rotor) at 1.8 m/s of maximum current velocity (FactorThis, 2010; MORILD, 2010)	Douziech et al. (2016)	Real. Recipe Method. ARDA software with ecoinvent database 2.2./Life cycle – construction dominant.	20.1 g CO_2/kWh
STRAFLO®	2016	Annapolis plant configuration. Bulb turbine with 7.6 m runner diameter with rotational speed of 50 rpm. 17.8 MW of output power at 5.5 m of hydraulic head and nominal discharge flow of 378 m^3/s (Goverment of Canada, 2019).	Douziech et al. (2016)	Real. Recipe Method. ARDA software with ecoinvent database 2.2./Life cycle – construction dominant.	3.9 g CO_2/kWh
DeepGen IV (TGL)	2015	3-bladed turbine, axial flow. Rotor with 18 f diameter, 1 MW of rated power at 2.7 m/s.	Walker et al. (2015)	Real. Worldsteel LCA methodology. University of Bath Inventory of Carbon and Energy (ICE) v2.0./Full life cycle (embodied energy).	34.2 g CO_2/kWh
OpenHydro	2015	tidal current turbine with horizontal axis rotor (16 m of diameter), without visible central axis (open center), with permanent magnet generator. 2 MW of rated power at 2.6 m/s	Walker et al. (2015)	Real. Worldsteel LCA methodology. University of Bath Inventory of Carbon and Energy (ICE) v2.0./Full life cycle (embodied energy).	19.6 g CO_2/kWh
Flumill	2015	twin Archimedes' screw turbine. Rotor diameter of 8 m, with rated power of 1 MW at 2.6 m/s (assumed value), the manufacturer did not report the nominal velocity.	Walker et al. (2015)	Real. Worldsteel LCA methodology. University of Bath Inventory of Carbon and Energy (ICE) v2.0./Full life cycle (embodied energy).	18.5 g CO_2/kWh
ScotRenewables (SR2000)	2015	2 bladed floating twin horizontal axis turbine, Rotor of 16 m of diameter with 2 MW of rated power at 3 m/s (XPRT energy, 2025)	Walker et al. (2015)	Real. Worldsteel LCA methodology. University of Bath Inventory of Carbon and Energy (ICE) v2.0./Full life cycle (embodied energy).	23.8 g CO_2/kWh
ORPC RivGen ®.	2014	3-blade helicoidal turbines, rotor with 1.4 m diameter. 25 kW at 2.3 m/s of current velocity	McCallum et al. (2021)	Real. Recipe Method, Simapro V.8.3 software./Operation stage.	69.97 g CO_2/kWh
Severn Barrage	2012	Theoretical plant with 216 Bulb turbines. Each turbine with runner diameter of 9 m, with rated power of 40 MW at 425 m^3/s and 8 m of Hydraulic head ("The Severn Barrage Project: general report," 1989).	Kelly et al. (2012)	Theoretical. SimaPro V 7.3. The impact assessment methodologies Cumulative Energy Demand v1.07 [14] and IPCC 2007 GWP 100a (with a timeframe of 100 years) [15] were used./Operation stage.	56.2 g CO_2/kWh
Crest Energy	2009	Theoretical tidal stream plant with 200 (22 m of diameter), without visible central axis (open center). 1.2 MW nominal power per turbine at 2.1 m/s of current velocity.(Bellvé et al., 2009; Crest Energy, 2009)	Rule et al. (2009)	Theoretical. SimaPro V 7.0. ISO Standard 14044./From construction to decommissioning and including maintenance.	1.8 g CO_2/kWh
Severn Barrage	2009	Theoretical plant of 8,64 GW of power generation with 216 Bulb turbines. 40 MW per turbine with rotor diameter of 9 m, operating with Hydraulic head between 3 and 4 m and flow 120-130 m^3/s (Black and Veatch, 2007; Nejc, 2019)	Woollcombe-Adams et al. (2009)	Theoretical. The emissions were calculated using data from UK Deparment of Energy (1989), Drax Power Ltd. (2004) and author's estimations./From construction to decommissioning.	5.7 g CO_2/kWh
SeaGen	2008	2-bladed double rotor axial flow turbine of 1.2 MW, with 16 m of diameters in each rotor. Current velocity for nominal power 2.25-2.5 m/s	Douglas et al. (2008a)	Theoretical. ISO Standard 14040. inventory of carbon &energy (ICE) – version 1.5 Beta./Manufacturing (materials dominant).	15 g CO_2/kWh
Seagen.	2008	2-bladed turbine. Twin axial-flow rotors with 16 m of diameter, 1.2 MW of rated power (0.6 MW each rotor) at 1 m/s.	Douglas et al. (2008b)	Real. University of Bath Inventory of Carbon and Energy (ICE)./Manufacturing (materials dominant)	15.0 g CO_2/kWh
Not reported	–	horizontal axis 3-bladed turbines, rotor with 20 diameters. 1-2 MW rated power at 4 m/s of current velocity.	Walker and Thies (2022)	Theoretical. Recipe Method, Simapro V.9.1.1.1 software./Manufacturing method, material and end-of-life treatment.	9714 kg CO_2/blade

we recommend specifying to AIs that the literature review must provide a direct web link to the document. Additionally, researchers could write verification questions, e.g., “Are you completely sure that the listed documents are real and verifiable through online or downloadable files? Please prove it.”

2.2. Processing stage

After the Input stage search, a result table was built with the following structure: year, title, authors, country, and reference. The results generated by the AIs were validated manually, ensuring that URLs or DOIs correspond to a real research document. The articles used in this work were carefully selected, with particular attention paid to whether keywords were included in the title and abstract of each document. In addition, it was ensured that each selected article provided detailed information on the used materials in tidal energy and their evaluation using the LCA methodology.

Each selected article underwent a thorough examination to identify the impacts generated by each material at different stages of the tidal energy process. Consequently, the materials used in the industry were identified and categorized according to the relevant engineering activities, encompassing manufacturing, construction, operation, maintenance, and decommissioning.

2.3. Output stage

After reviewing each research and technical document and identifying the material impacts on LCA categories, a screening process was conducted to assess the GHG emissions of tidal turbines, the most commonly used materials in tidal energy, the relationship between materials and LCA impact categories, and the material impacts in other marine technologies.

3. Results

Data mining was conducted on the information retrieved from the systematic literature review, considering the keywords defined in the input stage. The results showed 40 documents related to marine and river applications of stream turbines. The first group of selected documents was revised and screened to extract the information defined in the output stage.

3.1. Greenhouse gas emissions of tidal energy technology

The intensity of GHG has been widely adopted because it quantifies environmental efficiency by measuring CO2 emissions when a technology generates electricity (International Energy Agency, 2024). This parameter was adopted in the Paris Agreement not only to harmonize GHG emission reporting to monitor global progress, but also to motivate stakeholders and consumers to select the cleanest and most efficient technologies (United Nations, 2016). This research defined the period between 2008 and 2025 in the input stage of the methodology (literature survey) and found 17 studies related to GHG emissions in terms of Greenhouse Gas Emissions Intensity (GEI) of tidal turbines (Table 1).

Several turbine models and configurations were identified, including bulb, horizontal, and screw turbines; most of them were horizontal axial turbines (Table 1). The revised studies are categorized as real and theoretical, where real projects indicate that the plant was built, deployed, and operated, and theoretical studies mean that the results are derived from a hypothetical tidal plant. It was observed that LCA studies on real operating tidal plants, specifically the bulb turbines of the Annapolis plant, reported the lowest GEI, i.e., 3.9 g CO_2/kWh, followed by the Flumill twin Archimedes’ screw turbine with 18.5 g CO_2/kWh (Table 1). The highest GEI (69.97 g CO_2/kWh) in real projects was reported in the ORPC RivGen ®, which utilizes 3-blade helicoidal turbines (McCallum et al., 2021). The theoretical studies pointed GEI between 1.8 g CO_2/kWh and 56.2 CO_2/kWh related to the Crest Energy and Severn Barrage projects, respectively.

A moving average was conducted on the GEI reported data of real LCA studies on hydrokinetic turbines (Table 1), and the results showed a positive trend in the GEI values from 2015 to 2018 (Fig. 2). The aforementioned was possibly due to the increase in available information in GHG data and the improvement of LCA tools and methods. The recent studies were conducted with more and updated information not only of the utilized materials, but also on the related activities like manufacturing, construction, transportation, operation and maintenance. For example, Kaddoura et al. (2020) and Paredes et al. (2019a). In their literature review until 2019, listed the GEI reports of LCA studies, showing emissions between 37 and 56.2 g CO_2/kWh for the highest and 1.8-3.9 g CO_2/kWh for the lowest, which evidences that recent studies reported higher GEI. Also, Zhang et al. (2020) conducted a literature review of LCA studies on tidal and wave energy, and reported that there exist few studies that followed the ISO 14040 and 14044 standards, affecting their reliability in their conclusions.

3.2. Most used materials in tidal energy technology

The materials need to be acquired and transformed for the manufacturing, installation, operation, maintenance, and dismantling of tidal turbines. As a result, these activities generate impacts on human health, ecosystems, and resources (Walker and Thies, 2022; Rashedi et al., 2022). In this sense, Walker & Thies (2022) recommended the use of recyclable materials suitable for incineration and landfilling to reduce negative impacts (Walker et al., 2015).

The listed materials in Table 2 contribute to environmental impacts across the different life cycle stages of TET, including raw material extraction, manufacturing, installation, operation and maintenance, decommissioning, recycling, or final disposal. Twenty-four materials were found in LCA studies of TET, where the LCA category impacts are not individualized by each material (Table 2). The three most reported materials were steel, concrete, and copper. As seen in Table 2, there exists a lack of information of LCA studies in TET that focus the individualized effect of each material, several of these studies reported generalized impacts on components of support activities e.g., (Bianchi et al., 2024b).

According to Figs. 3 and 4 this research identified that cooper was the most polluting material, provoking the highest effects on the LCA categories and impacting all 18 categories, i.e, stratospheric ozone depletion, ionizing radiation, terrestrial acidification, freshwater eutrophication, human non-carcinogenic toxicity, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity. The second material with the most impact is steel, observed in six categories, i.e., fine particulate formation, ozone formation-terrestrial ecosystem, ozone formation-human health, land use, mineral resource scarcity, and human carcinogenic toxicity. The Glass Fiber Reinforced Plastic (GFRP) material showed the highest impacts in marine eutrophication, fossil resource scarcity, and water consumption. Carbon fiber led the global warming impact among all the assessed materials.

According to Rashedi et al. (2022a), steel is the main material constituting more than 70% of the total turbine mass, however, its contribution to the impacts on LCA categories like global warming and carcinogenic human toxicity is not clear, due to the large amount of steel required today (Paredes et al., 2019c). Copper is used in smaller proportions compared to other materials such as steel, however, it is the most negative contributor in acidification, eutrophication, and toxicity. Copper manufacturing emits a variety of materials like phosphate, that can generate eutrophication due to algal blooms caused by dumping, and tailings that generate toxicity effects due to poor management (Rashedi et al., 2022a).

Although steel and carbon fiber composites have higher environmental impacts than fiberglass composites, recyclable and bio-based products provoke lower environmental impacts. In addition, bio-based

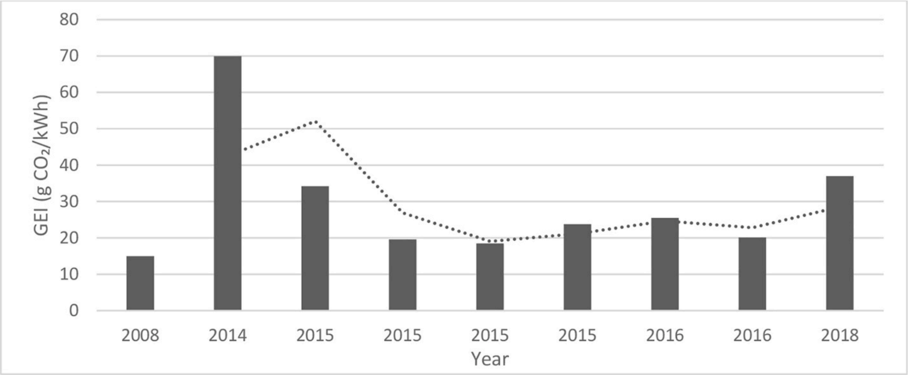

Fig. 2. GEI of hydrokinetic turbines reported in real LCA studies.

fibers represent an alternative option to replace carbon or glass fibers. These natural fibers have the lowest greenhouse gas emissions compared to the other options considered, and have relatively low environmental impacts on all evaluated measures (Walker and Thies, 2022).

Turbine blades are composed mainly of GFRP and, in some cases of Glass Fiber Reinforced Concrete (GFRC), which are the least recycled parts, mostly disposed in landfills or incinerated. The study of Walker & Thies (Walker and Thies, 2022) reported that recycling metallic and bio-based materials generate less impact compared to incineration or landfill. The used materials in TET need to be acquired and transformed for the manufacturing, installation, operation, maintenance, and dismantling of tidal turbines. As a result, these activities generate impacts on human health, ecosystems and resources, therefore, is recommended the use of recyclable materials suitable to incineration and landfilling to reduce negative impacts.

This research retrieved data from the literature to establish the relationship between the materials used in TET and LCA categories. The ReCiPe method was applied to characterize the main factors on a global scale (Huijbregts et al., 2017). These factors allowed the modeling of the impact pathways from the midpoint to the endpoint, then, 3 categories of the endpoints were identified as the final impact of the materials on LCA (Figs. 5 and 6). The pathways on Figs. 4 and 5 illustrate qualitatively where different materials contribute, through midpoint indicators, to the final impacts on human health, ecosystems, and natural resources.

The most required materials in the manufacturing process of TET are steel, cooper, stainless steel, concrete and cast iron (Fig. 5), hence, they generated 18 midpoint impacts. It was observed that steel and cooper were the ones with the highest impact on the water resources (freshwater and marine water). Concrete impacted primarily the ozone layer and atmosphere, and no relationship between cast iron on and LCA categories was identified, hence, it is assumed that hidden impacts of this material remain undisclosed.

The GFRP impacted 13 of 18 LCA midpoint categories and led three midpoint categories among all the materials (Figs. 3 and 4). The production of GFRP composite materials has negative environmental impacts, such as fossil fuel depletion and air pollution. According to this, it is urgent to conduct research on GFRP to reduce the impacts generated by the production process, also, the need to replace GFRP in TET is an alternative to mitigate these LCA impacts. Carbon fiber is considered a lightweight alternative for manufacturing turbine blades, which could reduce the environmental impacts. However, carbon fiber production generates more GHG than fiberglass (Rashedi et al., 2022a).

Fig. 7 presents the percentage distribution of midpoint impacts generated by each material. The water consumption reported in Fig. 4j shows that GFRP consumed 6000 m^3, making it the material with the highest impact in this midpoint category. Consequently, in quantitative terms and contribution distribution, GFRP leads this impact category with a 61% of contribution, followed by steel with 20% (Fig. 7). Steel dominates five midpoint impact categories, contributing nearly half of the total impact; for example, mineral resource scarcity with a 44% contribution. Copper dominates nine midpoint impact categories, with dominant contributions of 72%, 66%, and 65% in terrestrial ecotoxicity, marine ecotoxicity, and freshwater eutrophication, respectively. These results highlight the need to focus on steel, copper, and GFRP to reduce their environmental impacts through process optimization or the adoption of new eco-friendly substitutes.

3.3. material impacts in other marine technologies

Marine energy technologies must operate in adverse conditions like high corrosion, intense humidity, and the impact of waves and currents, which demands the use of specialized materials compared to traditional technologies such as solar, wind, geothermal and biomass. Uihlein (2016) conducted a literature review and reported the materials utilized for power take-off systems, shaft, gearbox, generator and other ancillary components used in ocean energy technologies. The main identified materials were steel, plastic, composites, aluminum, water, copper, rare earths, lead, PVC, polyethylene pipe, tin, platinum, nickel, concrete, and light fuel oil. The LCA impact categories in that study were climate change, acidification, ozone depletion, particulate matter/respiratory inorganics, Ionizing radiation, human health, human toxicity, cancer effects, photochemical ozone formation, freshwater eutrophication, marine eutrophication, terrestrial eutrophication, freshwater ecotoxicity, resource depletion, fossil and mineral.

Offshore wind energy (OWE) has components and mechanisms of operation similar to those of tidal turbines, like, blades, rotor, tower, generator, nacelle, among others. A recent study revealed serious negative impacts of the offshore wind technology on several LCA categories, including human health, ecosystems and resources (Rueda-Bayona et al., 2022a). The research revealed that materials such as steel and aluminum, concrete, fiberglass, resin and petroleum-based materials generated negative impacts and were associated with the highest energy consumption. OWE has been commercialized for several years; however, gaps still exist in the identification and quantification of the impacts on LCA categories, which urges research focused on new materials, eco-friendlier, and more sustainable materials to replace the traditional ones like steel and petroleum-based materials.

Rueda-Bayona et al. (2022a) performed a study focused in the OWE, and reported the related LCA impacts of several materials including metals, petroleum base materials, glass fiber, among others. The study highlighted those metallic materials had the most negative impacts on LCA categories, including GHG emissions and energy consumption. According to the research of Yuan et al. (2023b), copper used in OWE was the highest contributor to eutrophication impacts. Yang et al. (2018b), Burgess and Biswas (2021) and Brussa et al. (2023), demonstrated that steel is the largest contributing material to GHG emissions and has the highest energy consumption compared to other materials. In

Table 2
Reported materials utilized in Tidal Energy Technology.

Material	Number of referencing articles	Properties/Reference
Steel	9	7600 ton (Brussa et al., 2023) 907.8 ton (Burgess and Biswas, 2021a) No data (Paredes et al., 2019b) 442.37 ton (Rashedi et al., 2022b) No data (Rueda-Bayona et al., 2022b) 7850 kg/m^3; 5.55 ton (Walker and Thies, 2022) 42400 ton (Yang et al., 2018a) 9720 ton (Yuan et al., 2023a) 1264.7 ton (Bianchi et al., 2024b)
Concrete	7	2540 ton (Brussa et al., 2023) 2073.46 ton (Burgess and Biswas, 2021a) Paredes et al. (2019b) 876.43 (Rashedi et al., 2022b) No data (Rueda-Bayona et al., 2022b) No data 43000 m^3 (Yang et al., 2018a)
Copper	6	No data (Paredes et al., 2019b) 8.54 ton (Rashedi et al., 2022b) No data (Rueda-Bayona et al., 2022b) 700 ton (Yang et al., 2018a) 2630 ton (Yuan et al., 2023a) 8-12 ton (Bianchi et al., 2024b)
Cast Iron	6	410 ton (Brussa et al., 2023) 3.71 ton (Burgess and Biswas, 2021a) No data (Paredes et al., 2019b) 7.3 ton (Rashedi et al., 2022b) No data (Rueda-Bayona et al., 2022b) 0.55 ton (Yuan et al., 2023a)
GFRP	6	195 ton (Brussa et al., 2023) 51.65 ton (Rashedi et al., 2022b) No data (Rueda-Bayona et al., 2022b) 1900 kg/m^3; 2.5 ton (Walker and Thies, 2022) 520 ton (Yuan et al., 2023a) 520 ton (Bianchi et al., 2024b)
Stainless Steel	3	865.88 ton (Burgess and Biswas, 2021a) No data (Paredes et al., 2019b) 29.2 ton (Rashedi et al., 2022b)
CFRP	2	1200 kg/m^3; 1.02 ton (Walker and Thies, 2022) No data (Bianchi et al., 2024b)
Glass Fiber	1	2.5 ton (Walker and Thies, 2022)
Hybrid	1	1.96 ton (Walker and Thies, 2022)
Carbon fiber	1	1200 kg/m^3; 1.02 ton (Walker and Thies, 2022)
Bio-based	1	1.48 ton (Walker and Thies, 2022)
Flax fiber	1	1.48 ton (Walker and Thies, 2022)
Lithium	1	0.45 (Bianchi et al., 2024b)
Aluminum	1	6-8 ton (Bianchi et al., 2024b)
Cast iron	1	5-7 ton (Bianchi et al., 2024b)
Clean Steel	1	27.9 ton (Bianchi et al., 2024b)
Vinyl ester resin	1	5.2 ton (Bianchi et al., 2024b)
Plastic	1	No data (Bianchi et al., 2024b)
Gel coat	1	0.12 ton (Bianchi et al., 2024b)
Adhesive	1	0.36 ton (Bianchi et al., 2024b)
Lead	1	4.5 ton (Bianchi et al., 2024b)
polyethylene	1	2 ton (Bianchi et al., 2024b)
polypropylene	1	1.1 ton (Bianchi et al., 2024b)

addition, Burgess and Biswas (2021b) showed that steel affected all the LCA categories evaluated.

Considering the similarities in the technological components and activity stages between TET and OWE, and the experience of OWE industry (Rueda-Bayona et al., 2022a), we suggest to consider the following key points for TET:

- use timber and new composite and eco-friendly materials to replace iron, concrete, steel and aluminum.
- utilize natural fiber reinforcements and polypropylene (thermoplastic polymer) to increase the recyclability of the TET blades.
- consider applying chemical treatments to improve the mechanical properties of the main turbine components.
- verify that rare earth extraction for magnet components follows the social and environmental regulatory framework.

New materials that could replace the traditional ones in the OWE industry, may not only reduce LCA impacts but also improve the Annual Energy Production (AEP). In several phases of different marine technologies i.e., naval technology, floating offshore wind, wave energy conversion, materials generated significant effects across the 18 evaluated categories. Fig. 8 illustrates the impact of operation and maintenance (O&M) on abiotic resources. However, according to the literature, both the operation and maintenance (O&M) and the decommissioning stage (see Fig. 5) can mainly contribute to ozone depletion (Yuan et al., 2023b).

Paredes et al. (2019d) pointed out that the LCA of ocean energy technologies, including assembly, installation, operation and disassembly, has a negligible effect on global warming and on most of the evaluated categories; therefore, this assumption may indicate the scarcity of available information on LCA impacts.

4. Conclusion

This study provides an assessment of the impacts associated with the different stages involved in the manufacturing of materials used in tidal turbines, evaluating their effects on human health, ecosystems, and resources by explicitly linking material inventories to midpoint and endpoint indicators of the ReCiPe method within the Life Cycle Assessment (LCA) framework.

Partial results to date indicate that the materials used in the manufacturing stage represent the main critical point in the life cycle of all marine technologies. The most representative materials impacting different categories are steel, copper and GFRP. It is important to note that although copper constitutes a smaller proportion of the total mass of turbines compared to steel, it is the metal with the highest impacts across all LCA categories, with high negative impacts on freshwater eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, aquatic ecotoxicity, and non-carcinogenic human toxicity. In this sense, further LCA studies are recommended to better understand the impacts of copper across its life cycle stages and the mechanisms driving them.

On the other hand, bio-based materials are still under research; however, they have proven to be a viable alternative because they produce lower emissions in some categories. The contribution of cast iron was less than 5% in all impact categories, which suggests that this material deserves more research to enhance its properties and be considered a substitute for other more contaminant materials such as steel. Research on recycling materials and their LCA impacts should be intensified to prevent the use of new materials. Therefore, it is recommended that future work includes the experimental evaluation of bio-based materials to better understand their performance, limitations, and potential applications, as well as the modeling of materials such as cast iron.

Timber, natural fiber reinforcements and polypropylene (a thermoplastic polymer) emerge as promising materials to replace the most contaminant and widely used material in TET. This requires an optimization of the timber supply chain to reduce the high energy consumption associated with transportation, and the replacement of thermoelectric power plants or diesel-based machinery used in extraction. Research on natural fibers and new polymers must continue with the support of nanotechnology and nanomaterials, to enhance their performance, durability, reusability or final disposal.

The progress of the tidal stream technology will not only depend on the capability of the materials used to resist the environmental loads, i.e., waves, currents, wind, lightning, others, and corrosive attack, but also on the need to reduce LCA impacts for environmental sustainability. This research recommends that the academic community to follows the

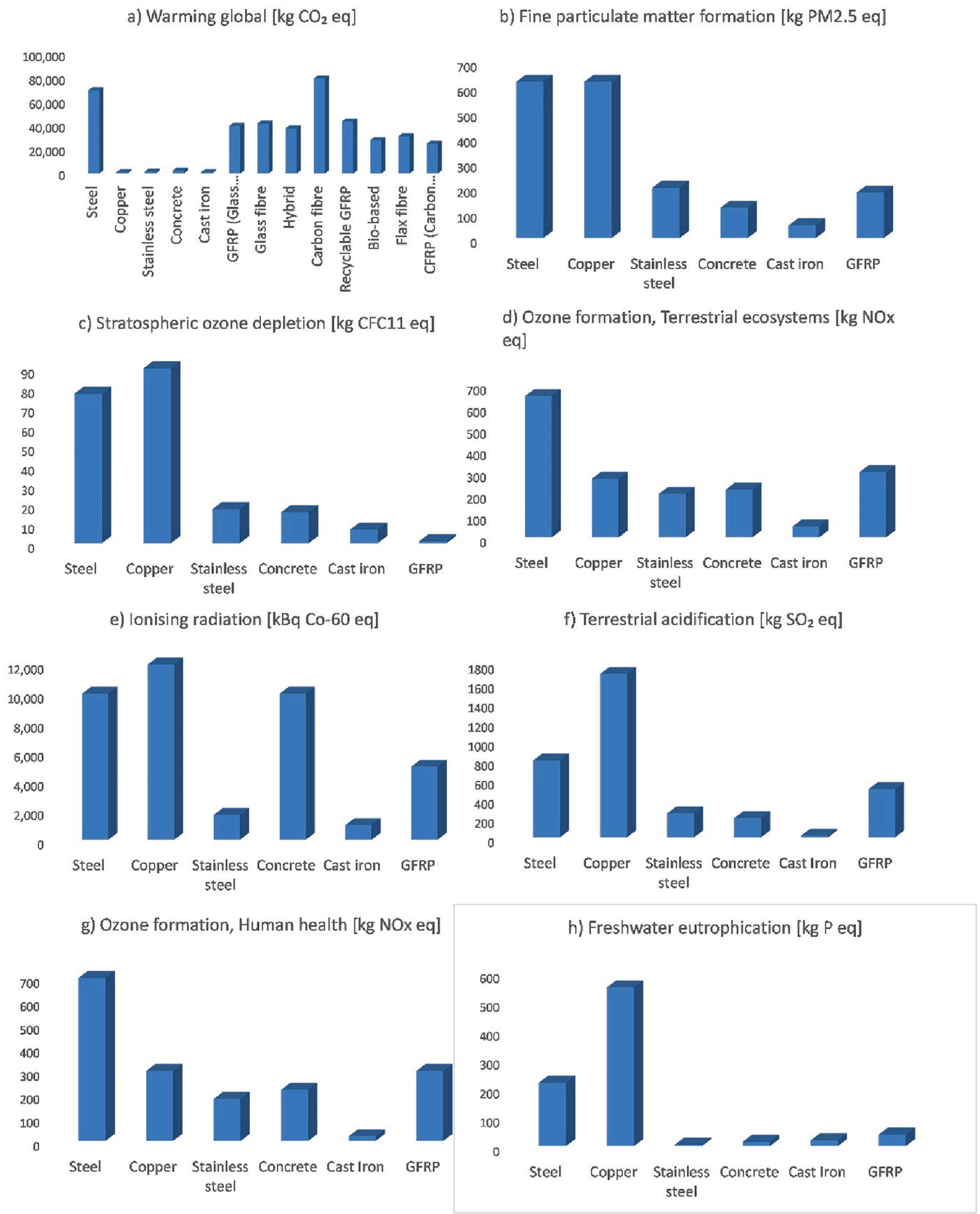

Fig. 3. Materials impacts on warming global, fine particulate matter formation, stratosphere ozone depletion, ozone formation, ionizing radiation, terrestrial acidification, ozone formation, fresh water eutrophication. Note: GFRP (Glass Fiber Reinforced Plastic), CFRP (Carbon Fiber Reinforced Plastic).

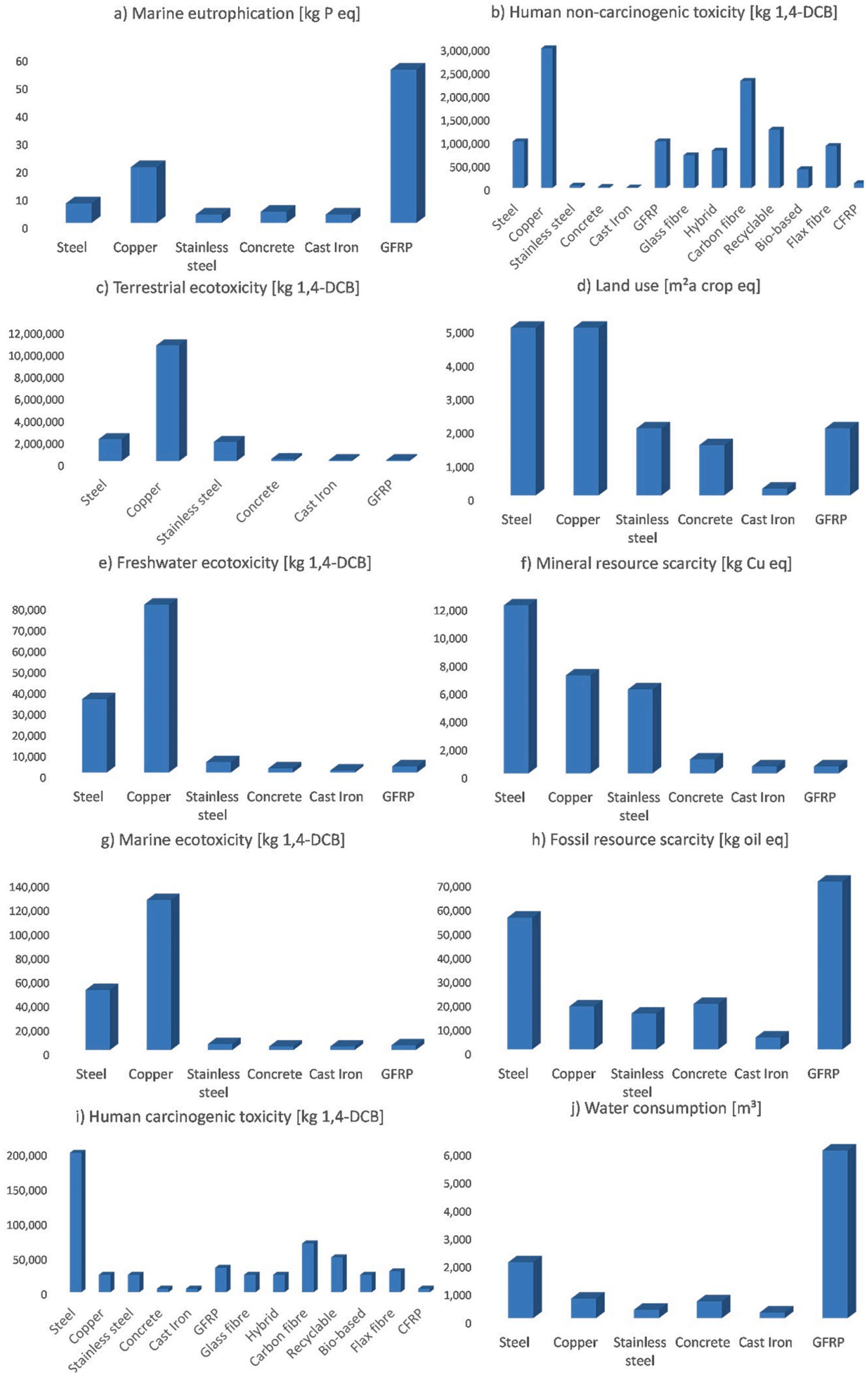

Fig. 4. Materials impacts on marine eutrophication, human non-cancerogenic toxicity, terrestrial ecotoxicity, land use, freshwater ecotoxicity, mineral resource scarcity, marine ecotoxicity, fossil resource scarcity, human cancerogenic toxicity, and water consumption. Note: DCB (Dichlorobenzene).

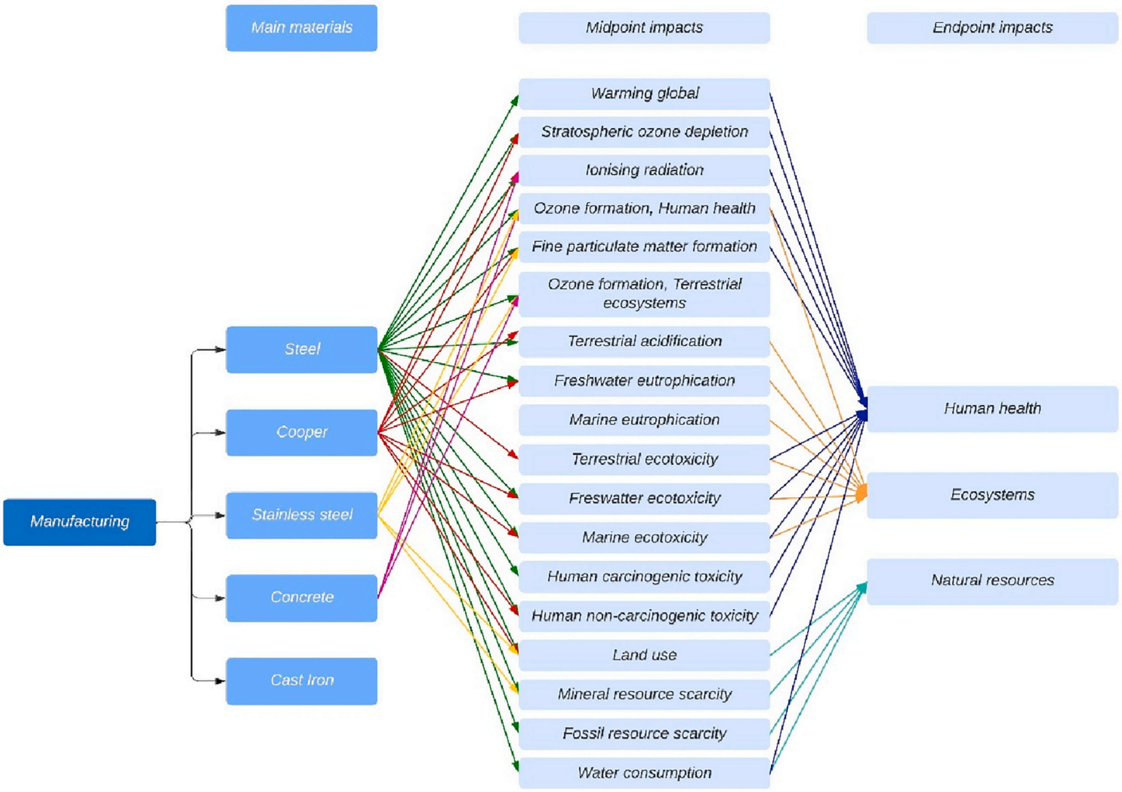

Fig. 5. Relationship between major metallic and non-metallic materials and the environmental impacts in midpoint and endpoint impact LCA categories.

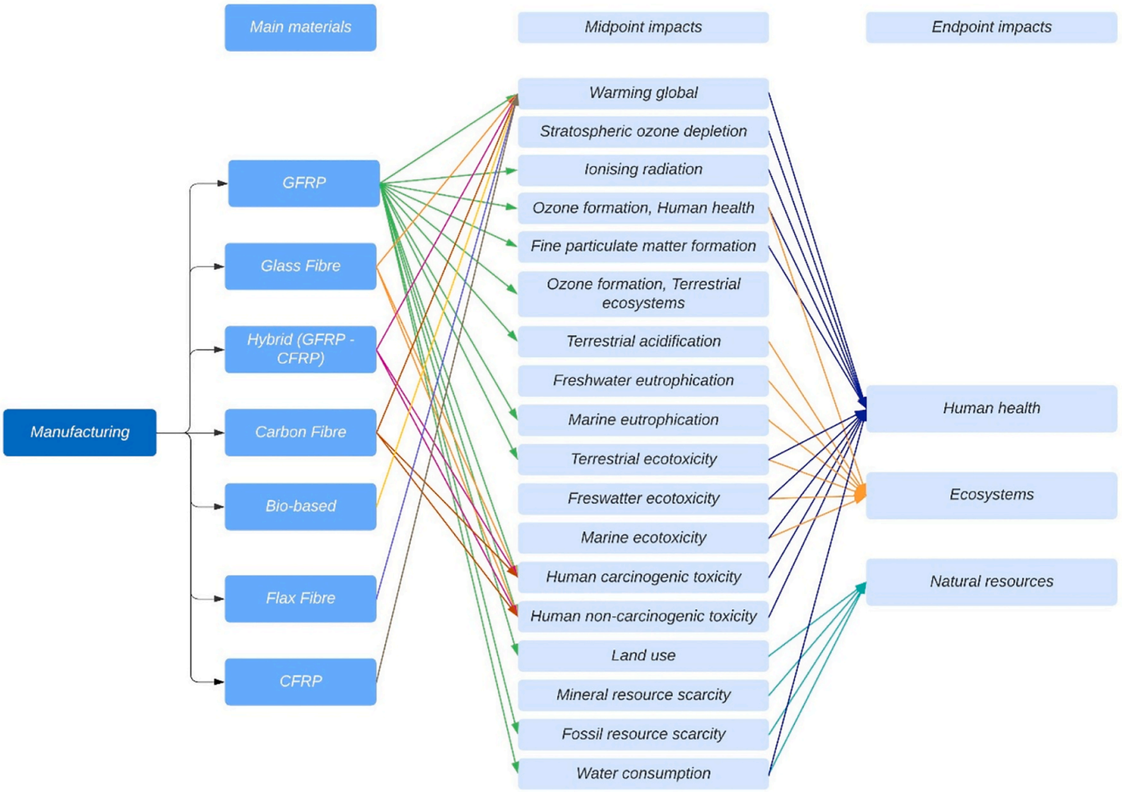

Fig. 6. Relationship between major biological-based and composite materials and the environmental impacts in midpoint and endpoint impact LCA categories.

same protocols or guidelines to establish objective values of GEI and LCA impacts to avoid discrepancies related to methodological errors. As a

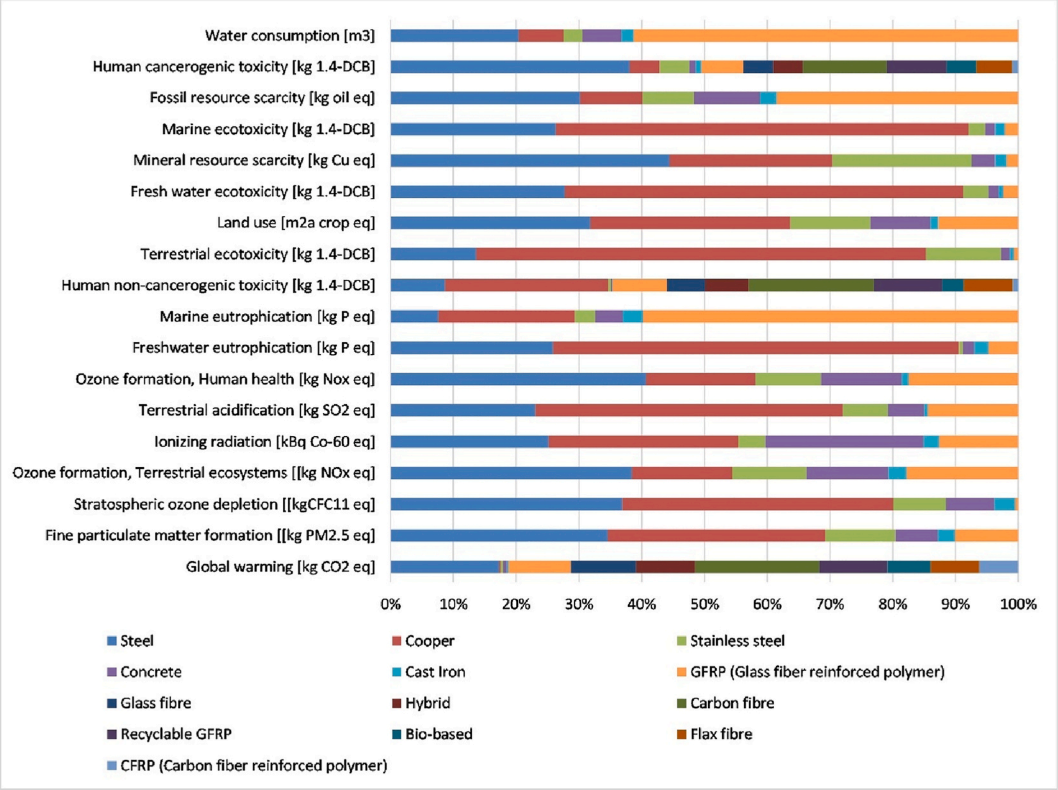

Fig. 7. Midpoint impacts and materials distribution in TET.

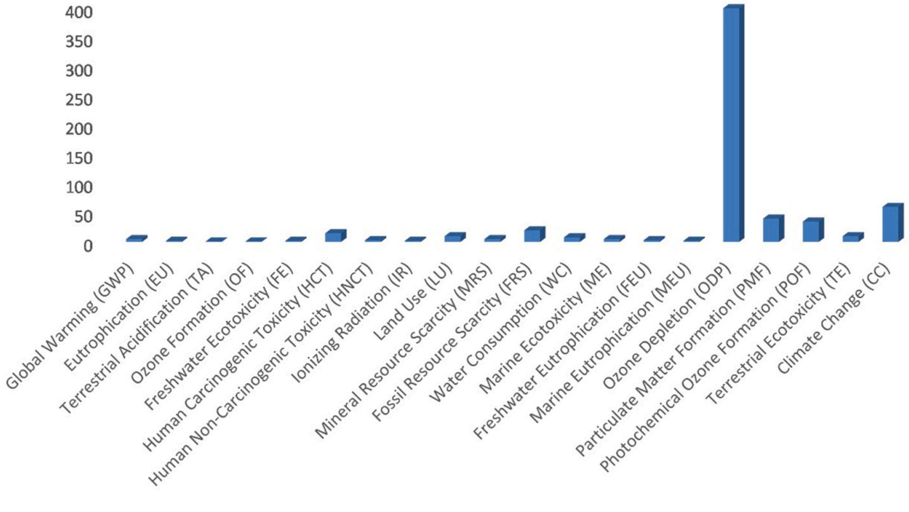

Fig. 8. LCA Impacts produced by the operation and maintenance stage in different marine technologies (i.e. naval technology, floating offshore wind, wave energy conversion).

result, this approach will provide a clearer picture of the negative impacts of the materials and associated activities of the tidal turbines, which will facilitate the sustainable development of the TRL and MRL of the tidal energy technology.

CRediT authorship contribution statement

Juan Gabriel Rueda-Bayona: Writing – review & editing, Writing – original draft, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Valery Osorio Franco:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Investigation, Formal analysis. **Juan José Cabello Eras:** Writing – review & editing, Writing – original draft, Investigation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Juan Gabriel Rueda-Bayona reports financial support was provided by Universidad del Valle. Juan Gabriel Rueda Bayona reports a relationship with Universidad del Valle that includes: employment and funding grants. 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.

Acknowledgments

The authors offer thanks to Universidad del Valle for funding this study through the research project 1410.

Data availability

Data will be made available on request.

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Update

Cleaner Production Letters
Volume 10, Issue , June 2026, Page

DOI: https://doi.org/10.1016/j.clpl.2026.100139

Cleaner Production Letters 10 (2026) 100139

Contents lists available at ScienceDirect

Cleaner Production Letters

journal homepage: www.journals.elsevier.com/cleaner-production-letters

Corrigendum to "Identifying materials in tidal energy technology and their effects to human health, ecosystems, and resources: A life cycle assessment perspective" [Clean. Prod. Lett. 10 (2026) 100137]

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The authors regret < to complement the acknowledgments>.

The authors would like to apologise for any inconvenience caused.

The updated acknowledgments are:

This work was supported by the Government of Colombia through project SGR BPIN 2024000100089 and to Universidad del Valle through the research project CI 71410.

DOI of original article: https://doi.org/10.1016/j.clpl.2026.100137.

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https://doi.org/10.1016/j.clpl.2026.100139