Sustainable Materials and Technologies 46 (2025) e01663

Contents lists available at ScienceDirect

Sustainable Materials and Technologies

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

Why hybrid composite materials? Findings from a systematic literature review of life cycle assessments

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ARTICLE INFO

Keywords:
Hybrid composite materials
Life cycle assessment
Systematic literature review
Multi-indicator environmental gains
Global warming

ABSTRACT

The article explores the relevant environmental issues of hybrid composite materials, that are defined as those systems in which two reinforcing or filling materials are added to a matrix, or a reinforcement or filler is added to a blend of matrices. To that end, a systematic literature review of Life Cycle Assessments (LCAs) in the field was carried out by the authors according to the PRISMA model, given that LCA is internationally recognized to be a scientifically-based valid methodology for assessing and improving sustainability issues of products and services. Web of Science (WoS) and Scopus were used to perform the bibliographical search, those are globally recognized to be the most comprehensive databases of peer-reviewed journals and, so, to store the broadest range of scientific articles.

The analysis of literature on the field of the lifecycle assessment (LCA) of hybrid materials have shown that this is a new path still to be explored. While LCA is widely used for the assessment of environmental properties of different materials and applications, to date only few papers apply this methodology to assess the lifecycle of hybrid materials.

Results retrieved have been combined to obtain the core works assessed in this review, finding that currently the literature about the application of LCA methodologies for assessing the impacts of hybrid composites is very limited, with not many references found to date, and thus there is huge potential for future growing in this path.

1. Introduction

Hybrid materials or hybrid composites are defined as those systems in which two reinforcing or filling materials are added to a matrix, or a reinforcement or filler is added to a blend of matrices [1]. These combinations of materials provide a set of advantageous properties over conventional composites, including balanced strength and stiffness, membrane properties, while also allowing for costs reduction while widening versatility [2,3]. Such enhanced properties have expanded in recent years the range of hybrid composites applications, including the automotive, aerospace, medical, electrical, civil, and marine industries [1,4–9]. This extensive range of properties and the different approaches to getting these hybrid materials make this multidisciplinary field highly appealing and fast growing. Issues such as compatibility, interfaces, stress transfer, and homogeneity are the focus of research and development work, while the analysis of lifecycle of such materials appears as one challenge to still envisage, as highlighted in a recent review by Ismail et al. [2]. Special attention needs to be paid to the downstream phases of maintenance, repair, and end-of-life treatment. The higher complexity of these materials makes it also more difficult to treat once the products arrive to the end of life.

Life cycle assessment (LCA) can make a valuable contribution in that regard, as it can be used to determine the major environmental impacts associated with each phase of the composite's life cycle, which means from preparation and acquisition of the composing raw materials, through their mixing into the composite, up to the end-of-life of the composite itself [9,10]. Those data on environmental impact can be considered to be useful in a wide prospective that includes, for example, the business economic one, with specific regard to the reporting activity and the internal management control decision process.

As an internationally-recognized, scientifically-based multi-indicator tool, LCA would help determine and compare the environmental

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https://doi.org/10.1016/j.susmat.2025.e01663
Received 29 July 2024; Received in revised form 19 May 2025; Accepted 15 September 2025
Available online 16 September 2025

impacts of such hybrid materials to support their optimal selection. However, to this review's authors' knowledge, not so many works among those available in the specialized literature have performed an in-depth proper environmental assessment on composites, as those were just limited to exploring the better environmental sound of bio-based composites [11]. However, several researchers have recently started wondering about the sustainability of different materials, including polymers and composites. Whether the use of biobased or biodegradable materials is enough to ensure their sustainability is the research question that they posed themselves [12–15]. Some authors concluded that the production of materials from first-generation biomasses is someway penalizing for their environmental profile, due a set of environmental aspects, that includes fuel and water consumption, fertilizer and pesticide use, soil occupation, and so on, [16–18]. Others pointed out, in fact, that the use of waste and by-products streams is a more environmentally preferable alternative [13,19–22]. For instance, Le Duigou et al. [23] have performed a comparison between flax and glass fiber production, obtaining favorable results for flax, despite the needs of watering and fertilizing, mainly due to the high energy consumed in the glass fiber production. Overall, their study puts emphasis upon reducing chemical fertilizer applications or using biofertilizers in partial or total replacement, so as to the eutrophication impact, and upon searching for - and holistically testing - solutions aimed at reducing energy use in the glass fiber production system. Different lignocellulose fibers show lower fertilization needs (such as kenaf or ramie [24]), and the use of waste streams or by-products also appears as a suitable alternative for this purpose. In this line, Operato et al. [19] have recently analyzed the environmental behavior of polylactic acid (PLA) composites reinforced with lignocellulose fibers: kenaf fibers and pine-needles. The use of these two lignocellulose materials allowed for a comparison between a crop (kenaf), which needs for fertilizers and fungicides (although in lower extend than other natural fibers), and the pine-needles, naturally occurring and generally considered as a waste. For the assessment, the authors took into account all the key steps of the production system investigated, that is, from raw material preparation and supply to fiber obtaining (washing, drying and milling for pine-tree needles; decortication is added to kenaf processing), compounding and granulation to obtain the composite pellets. As a result of this research work, authors have found that the composites have a lower environmental impact than the neat PLA, with further advantages when using the pine-tree needles, mainly due to a reduction in toxicity, because of the use of fertilizers in the case of kenaf cultivation. Besides, the increase in mechanical properties of the composites due to the fiber incorporation allows for a further reduction of PLA to achieve a similar performance, which provides further benefits. In particular, the use of 40 % kenaf resulted in an increase of 50 % of the flexural modulus and a reduction of 50 % in global warming potential (GWP), 40 % in terrestrial ecotoxicity potential (TETP), 25 % in eutrophication potential (EP) and 10 % in ozone depletion potential (ODP); the incorporation of pine tree needles resulted in lower mechanical properties (still, a 30 % improvement compared to neat PLA), and similar levels of reduction of GWP, TETP and OPD, with further reduction of eutrophication, over 30 %. Similar conclusions were obtained by Rodríguez et al. [5], working in this case with banana fibers, which are considered as a waste from banana food production; the composites with higher fiber content resulted in a better environmental performance. Ingrao et al. [20] have analyzed the influence of adding spent coffee waste into a polybutylene succinate (PBS) matrix, finding that an increase in the loading of the filler results in better environmental performance. However, if the characterization of the composite from the mechanical point of view is added, 40 % of the spent coffee ground appears as optimal, with increases of almost 100 % in elastic modulus, better dimensional stability, and higher composting rate [22], and an overall decrease of carbon footprint and energy demand of the composites, despite the slight increase in energy consumption from the waste processing, due to the reduction in the PBS content.

Despite these results, it should be emphasized that each material's system should be analyzed on an individual basis; it is generally accepted that the use of wastes would improve the sustainability of the process, while the analysis performed by Chen et al. [25], related to the valorization of potato wastes from starch production, has shown an improvement at the social and economic level, but a worsening in the environmental behavior of the obtained composites (PHA and PLA based). As a matter of fact, if on one side the use of such a residual biomass for composite material production implies a valorization of residues and an economic benefit, on the other side the need for drying the starch for its later processing is responsible for increased energy consumption and resultant GHG emissions. Therefore, the use of alternative energy sources for this drying stage or a process that allows for the use of the material skipping that stage would pose a considerable reduction in such a factor, and increase the overall benefit of the approach proposed in this research work.

Finally, Wouterszoon Jansen et al. [26] proposed the implementation of a hybrid strategy, considering both the use of materials from biological origin and the reuse and recycling of technical materials, as the best strategy to overcome the limitations of each of them separately. Their research, focused on building materials, showed that lifecycle costing and lifecycle assessment not always align (an option yielding better results in costs not always provide good results in terms of environment), and so combining both options would allow arriving to a compromise solution, which they call "circular performance". This research allows concluding that different approaches (lifecycle assessment, material flow analysis and lifecycle costing) should be undertaken in order to maximize the benefits of the novel materials and processes developed, reducing the environmental footprint (LCA) without decreasing lifespan or increase costs (LCC).

Furthermore, authors claimed about the cost effective, recyclable, and biodegradable character of hybrid composites containing natural lignocellulose fibers [1], although their potential recyclability and biodegradability merits have not yet been fully assessed. On the other hand, to the authors' knowledge, the specialized literature lacks LCAs of hybrid composites, and the potential benefits of such materials at the environmental, and socioeconomic levels have not been in-depth studied. The range of composite materials available is so wide that further studies addressing the sustainable performance of such materials are needed, considering the triple bottom approach: environmental, social and economic aspects should be assessed following a systematic LCA-based approach.

Under this perspective, this article was aimed at systematically reviewing and building upon the literature on LCAs of hybrid polymer-based composites, to highlight what has been done thus far, what are the environmental indicators that are most representative of the sector, and what are the improvements that have been proposed or made for its greening.

To the authors' knowledge such a systematic literature review (SLR), going more in-depth of the environmental burdens of such as new and promising materials as the hybrid ones are have not been developed before. Several other reviews have, in fact, been published thus far, but they were not SLRs and were mainly focused upon assessing their mechanical performance of composite materials, but did not analyze their environmental behavior [12,27–30]. Some of them are very recent, such as the works by Dutta et al. [27], which performed an assessment of the composites obtained from chicken feathers as a biopolymer or as a filler, or the one by Khan et al. [28], devoted to the analysis of bamboo-PLA composites. However, these, or the works by Das et al., Ortega et al. or Kelly-Walley and collaborators [29–31] analyzed, from different perspectives, the possibilities of preparing polymer-based composite materials by different processing technologies from various sources, considering wastes as promising raw materials to reduce their environmental footprint: however, the environmental perspective has not been analyzed, or it has in a superficial way.

Hybrid materials have gained popularity among industry and academy more recently, which explains why the associated literature was found by this article's authors' team to be limited compared with traditional composite materials, with special regard to the assessment of their environmental profile. In addition to this, it can be considered that the specialized literature is currently lacking systematic reviews in this hybrid-material field, which can be motivated by the relatively youth and complex process to perform them, in comparison to other forms of literature review [32,33]. This is the gap that, overall, the authors wish to highlight and start filling with this first review article, with the aim of taking stock of the situation, and creating the knowledge base for future environmental assessments. In summary, the authors believe that this SLR might contribute to encouraging the design and development of sustainable, innovative, high-performance hybrid composites which, thus, can find their share on the market of green products, contributing to the achievement of sustainable development goals, filling that gap by stablishing a literature framework based on the PRISMA model.

2. Materials and methods

Considering their increasingly-widespread use, a Systematic Literature Review (SLR) of LCA applications in the field of hybrid composites was performed by this team of authors, for an up-to-date exhaustive overview of the environmental hotspots in their supply chains and life cycles (search performed in May 2024).

Conceived as such, the SLR may serve as the essential knowledge basis that can be of support for LCA practitioners to perform future assessments that can guide decision and policy makers towards promotion of sustainable composites.

The SLR was performed following duly the PRISMA model proposed by Page et al. [34], with the main aim of overviewing the current and likely-future production trends of hybrid composites from an environmental perspective. It was applied because, according to Snyder, Page and Crovella and collaborators [32,34,35], it provides an explicit, rigorous, and reproducible design to explore and build upon the current large body of previously-published work from researchers, scholars, and practitioners.

Under this perspective, the authors of this SLR believe that it might deliver useful insights on:

- the environmental burdens of the sector, and the improvements that can be made for enhanced sustainability of its environmental sound; and
- the key methodological aspects related to LCA applications.

Web of Science (WoS) and Scopus were used to perform the bibliographical search, as those are globally recognized to be the most comprehensive databases of peer-reviewed journals and, so, to store the broadest range of scientific articles [36,37]. It is also worth highlighting that there are lots of those journals that investigate the merits of material, commodity, and environmental science, along with industrial engineering, that the authors see to be well connected with the core research theme object of this SLR. Therefore, following previously published SLRs, like those from Zingale et al. [37] and Crovella et al. [32], the authors merged the aforementioned databases for the sake of increasing the probability of detecting all the relevant contributions in the field, and of providing a high level of rigor for the search and selection of the review sample manuscripts.

To create a final sample of articles papers that was consistent with this SLR's aim and scope and to produce relevant results, the authors made a set of Boolean searches, that combine combining pre-determined representative keywords (see Table 1) with operators, such as 'AND'.

The search queries made were summarized in Table 1, that allow to retrieve a total of 3091 records on Scopus and 1205 on WoS that were then subjected to the following screening steps:

Table 1
Number of papers retrieved from Scopus and WoS.

Keywords	Scopus	WoS
Sustaina* AND "hybrid composite"	1168	442
Sustaina* AND "hybrid material" AND composite	479	197
LCA AND "hybrid composite"	14	7
LCA AND "hybrid material"	55	9
LCA AND composite AND hybrid	78	70
Lifecycle AND "hybrid composite"	11	0
Lifecycle AND "hybrid material"	14	1
Lifecycle AND hybrid AND composite	36	22
Environment* AND impact AND "hybrid composite"	750	355
Environment* AND impact AND "hybrid material"	486	102

1. Double-count of articles indexed both in Scopus and WoS was avoided, by removing the existing duplicates.
2. Only peer-reviewed articles written in English were considered;
3. Articles published in book chapters and conference proceedings were not reviewed because they are often not easily downloadable;
4. The authors carried out an initial screening of the articles based upon their title and abstract, to better understand the research themes investigated and the adherence to the objectives of this review;
5. The articles remaining from application of criteria from 2 to 4 were selected for the in-depth analysis of their relative full texts, to create the eligible review sample (ERS);
6. The reference lists of the ERS articles were scanned through, to search for any additional articles.

The number of works retrieved from both databases using different combinations of keywords are summarized in Table 1.

In the flow diagram of Fig. 1, the authors depicted all the screening steps for creation of the ERS. The latter, through application of the aforementioned inclusion/exclusion criteria in all selection steps (i.e. from record identification to evaluation and inclusion), resulted to be formed by twenty, out of the over 4000 records initially detected in both databases.

As shown in the figure, after removing duplicates (same works appearing in the different searches), a total of 2433 works result. Considering only papers published in English and excluding conference papers, reviews or book chapters, as indicated above, the final list is reduced to 1269 references. From this first list, the authors' keywords were analyzed in order to refine the results and remove those works not related to the topic; for instance, some works contain "ibuprofen", "energy conversion" or "cation selectivity" as keywords; as a result, 467 papers were selected and abstracts were analyzed. From these, the abstracts reading allowed to determining that part of the works still remaining after the first filters applied were found to be dealing with different applications of polymers, composites, or hybrid materials, but not with the lifecycle or the environmental impact of such materials, and, therefore, out of the scope of this review. Once all these documents were removed from the list, the final selection of the already-cited twenty documents arouse (Table 2). It is noticeable that, despite the huge number of works appearing in the databases search, the use of keywords and automatic tools is still not completely refined. Particularly, many works deal with sustainability issues, but not with hybrid materials, or are related to hybrid technologies (or materials), but the analysis of their environmental behavior is not assessed in the work. As said, most retrieved works were discarded, as they were found by the authors as dealing with completely different topics, such as hybrid geopolymers for environmental applications or graphite/lignin electrodes for batteries. These are indeed hybrid composites with environmental applications, but none of these works deal with environmental analysis, LCA, carbon footprint, or sustainability. For convenience of the readers and for completeness of this review article, the twenty documents composing the final review sample were listed by the authors in Table 2, where it is clearly shown that they were published in the period

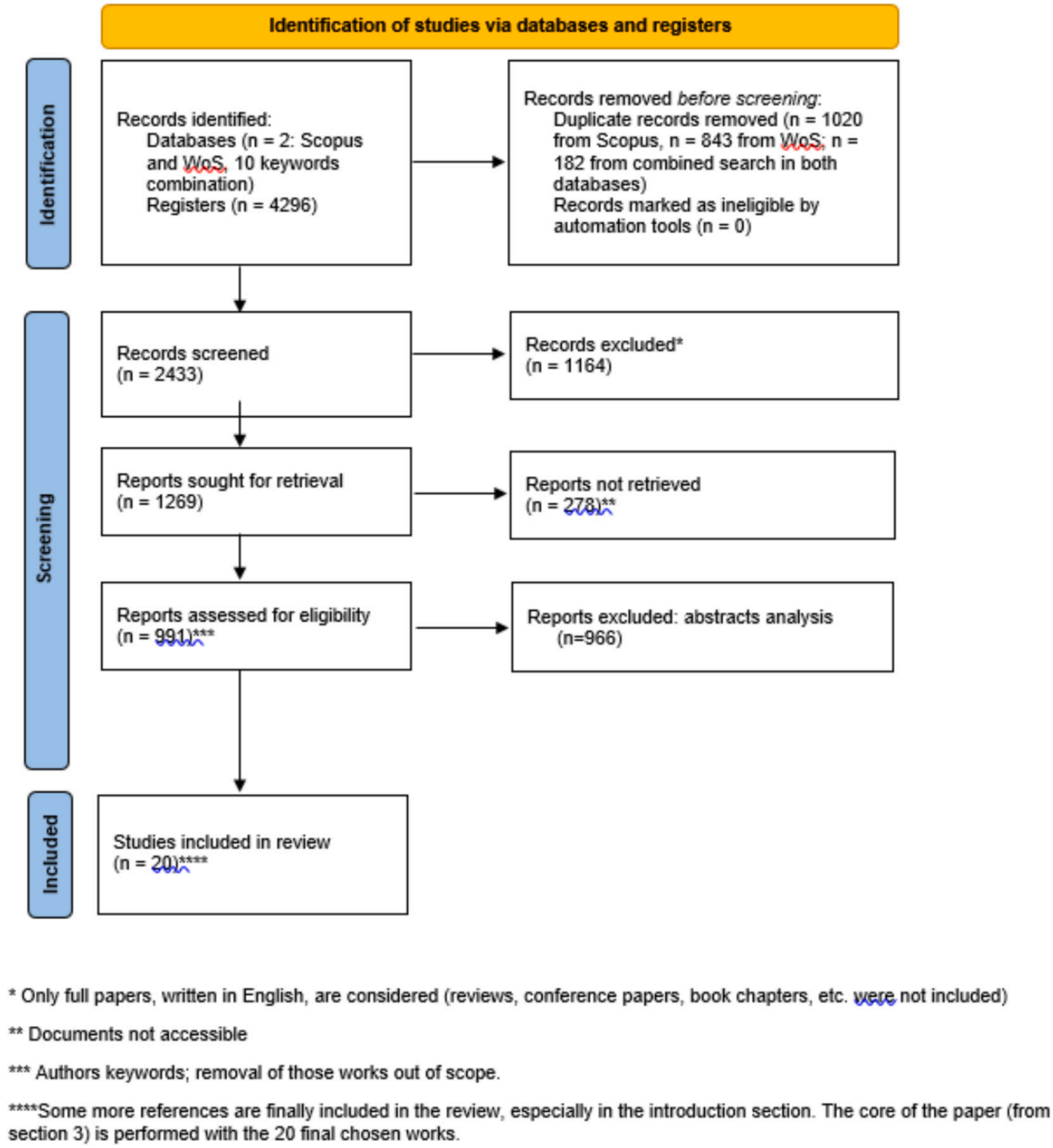

Fig. 1. PRISMA flowchart summarizing the literature findings.

2009–2022, thus demonstrating the relatively recent interest on this topic, despite the great concern on the search of more sustainable materials.

From Table 2, there is evidence that the first article of the created ERS was published in 2009, and an annual production of about three articles was noticed. This is in clear contrast to the trend on LCA publications, which grows yearly, showing the specificity of the search performed, and the need of bringing efforts to the study of the impact of such hybrid materials. Composite materials and their life cycles have been more widely explored in literature, also showing a rising number of publications in this area. The relative novelty of hybrid composites, together with the lack of consistent data, hinder the adoption of LCA methodologies for such materials. In any case, some authors have already started working on this field, and excitingly paved the way for understanding the environmental and social effects of those materials: the twenty articles object of this SLR are an example of that showing, overall, how important it is to complement mechanical and/or physical-chemical characterization studies with environmental assessments.

In order to obtain a first insight on the connections between the ERS articles, a co-occurrence network analysis of the keywords indicated in those articles was performed by this team of authors using the VOSviewer software [38], as depicted in Fig. 2. The nodes represent the keywords that are interlinked and form the network, and were obtained from adding the ERS-articles' keywords with the Scopus-indexed ones. The co-occurrence relations between pairs of keywords are shown by the edges of the network. The nodes have a size that is dependent upon the number of documents in which the keyword occurs, whereas the co-occurrence relations and their strength are given by the number of articles in which the linked keywords occur together [38,39]. The network was obtained using a full counting analysis method and setting the minimum number of a keyword occurrences at 1, so that all 105 keywords could be included. If using the online tool Inciteful XYZ, consisting in a literature connector, and connecting the first and last paper published from the list in Table 2, a total of 73 papers appears as a result of the search; however, an analysis of such documents results in only 21 of them with the keyword "hybrid", from which only a few contain data relative to the environmental behavior of them. Besides, this tool also provides the connections among the different works, leading to a similar graph to that obtained from VOSviewer (Fig. 2). As observed, the most significant term is characterization, followed by hybrid material or synthesis. Interestingly, natural fiber and life cycle assessment are in the same level of relative importance, highlighting the relationship usually

Table 2
Summary of works that constitute the core of the review about hybrid composites and their environmental behavior.

Authors	Publication year	Article title
De Rosa I.M. Santulli *C. sarasini* F. Valente M.	2009	Effect of loading-unloading cycles on impact-damaged jute/glass hybrid laminates
La Rosa A.D. Cozzo G. Latteri A. Recca A.	2013	Life cycle assessment of a novel hybrid glass-hemp/thermoset composite
Pandita S.D. Yuan X. Manan M.A. Lau C.H.	2014	Evaluation of jute/glass hybrid composite sandwich: Water resistance, impact properties and life cycle assessment
Delogu M. Zanchi L. Dattilo C.A. Pierini M.	2017	Innovative composites and hybrid materials for electric vehicles lightweight design in a sustainability perspective
Akhshik M. Panthapulakkal S. Tjong J. Sain M.	2017	Life cycle assessment and cost analysis of hybrid fiber-reinforced engine beauty cover in comparison with glass fiber-reinforced counterpart
Mastura M.T. Sapuan S.M. Mansor M.R. Nuraini A.A.	2017	Environmentally conscious hybrid bio-composite material selection for automotive anti-roll bar
Khoshnava S.M. Rostami R. Ismail M. Rahmat A.R.	2018	A cradle-to-gate based life cycle impact assessment comparing the KBFw EFB hybrid reinforced poly hydroxybutyrate biocomposite and common petroleum-based composites as building materials
Hay R. Ostertag C.P.	2018	Life cycle assessment (LCA) of double-skin façade (DSF) system with fiber-reinforced concrete for sustainable and energy-efficient buildings in the tropics
Bachmann J. Yi X. Gong H. Martinez X.	2018	Outlook on ecologically improved composites for aviation interior and secondary structures
Akhshik M. Panthapulakkal S. Tjong J. Sain M.	2019	The effect of lightweighting on greenhouse gas emissions and life cycle energy for automotive composite parts
Qiang T. Chou Y. Gao H.	2019	Environmental impacts of styrene-butadiene-styrene toughened wood fiber/polylactide composites: A cradle-to-gate life cycle assessment
Ricciotti L. Occhicone A. Petrillo A. Ferone C.	2020	Geopolymer-based hybrid foams: Lightweight materials from a sustainable production process
Chen W. Oldfield T.L. Cinelli P. Righetti M.C.	2020	Hybrid life cycle assessment of potato pulp valorisation in biocomposite production
Demertzi M. Silvestre J.D. Durão V.	2020	Life cycle assessment of the production of composite sandwich panels for structural floor's rehabilitation
Nguyen W. Martinez D.M. Jen G. Duncan J.F.	2021	Interaction between global warming potential, durability, and structural properties of fiber-reinforced concrete with high waste materials inclusion
Rodríguez L.J. Ospina S. Ribeiro I. Peças P.	2021	Banana fiber-biocomposite applied to bottle lid case - life-cycle engineering model for material selection
Stelzer P.S. Cakmak U. Eisner L. Doppelbauer L. K.	2022	Experimental feasibility and environmental impacts of compression molded discontinuous carbon fiber composites with opportunities for circular economy
Wouterszoon Jansen B. van Stijn A. Eberhardt L.C.M. van Bortel G.	2022	The technical or biological loop? Economic and environmental performance of circular building components
Tighnavard Balasbaneh A. Sher W. Yeoh D. Koushfar K.	2022	LCA & LCC analysis of hybrid glued laminated Timber–Concrete composite floor slab system
Wegmann S. Rytka C. Diaz-Rodenas M. Werlen V.	2022	A life cycle analysis of novel lightweight composite processes: Reducing the environmental footprint of automotive structures

established between the origin of the material and its sustainability, despite the relatively low number of documents dealing with that assessment in detail.

The ERS articles have been published in different journals, being the *Journal of Cleaner Production* the only one repeated in the list, with four articles published. According to the authors, such a finding confirms the dominating role that this journal has in the field of LCA-applications to sectors like bio-based material science and engineering due to the increasingly large number of publications that they welcome.

If grouped by sectors, publications are equally distributed with materials and composites, building, clean production, environment and sustainable development. The analysis of authors' keywords led to the results showed in Fig. 3. LCA is the most repeated keyword, followed by bio-based materials, and composites. The term "bio-based materials" summarizes natural fibers and bio-based matrices (natural fibers accounts for one third, that is, 6 %, while bio-based matrices appear in the other two thirds), and gives an idea of the relevance on the materials origin in its environmental performance. Building appears as one of the most relevant applications, and light-weighting as an outstanding property for these materials.

All the above stated, in the two sections following, the aforementioned selected papers were reviewed in terms of key objectives and findings, distinguishing between whether LCA was limited to DW cultivation or extended to the production of DW-derived foods. Thereafter, Section 2.3 was conceived by this team of authors to contain the relevant remarks based on the review's findings.

3. Objectives and findings of the twenty ERS articles

As already mentioned in the introduction section, very few papers deal with the analysis of the environmental, societal and economic impacts of hybrid composites. Besides, the review on hybrid composites containing natural fibers, performed by Ismail and collaborators [2], point out the study of environmental impact as one the challenges to still envisage; more than one year after that review paper, the topic continues to be mostly unexplored. The papers found in the literature about this topic can be mainly classified according to the system studied: two fillers/reinforcements in a matrix, or a filler/reinforcement in a blend of matrices. Table 3 summarizes the environmental benefits achieved by the use of composite materials based on different types of fillers and matrices, both bio-based and man-made. From the figure there is evidence that those benefits are mainly related to global warming, photochemistry oxidation, acidification and eutrophication, human toxicity, and ozone depletion. A lack of a standardized procedure for the environmental analysis can be observed, with different authors using different functional units and determining different environmental parameters, therefore making it difficult to establish comparisons between different materials combinations.

Qiang et al. [40] analyzed the composites made of PLA and wood fibers toughened with styrene-butadyene-styrene (SBS), finding that the incorporation of this last polymer resulted in a reduction in the

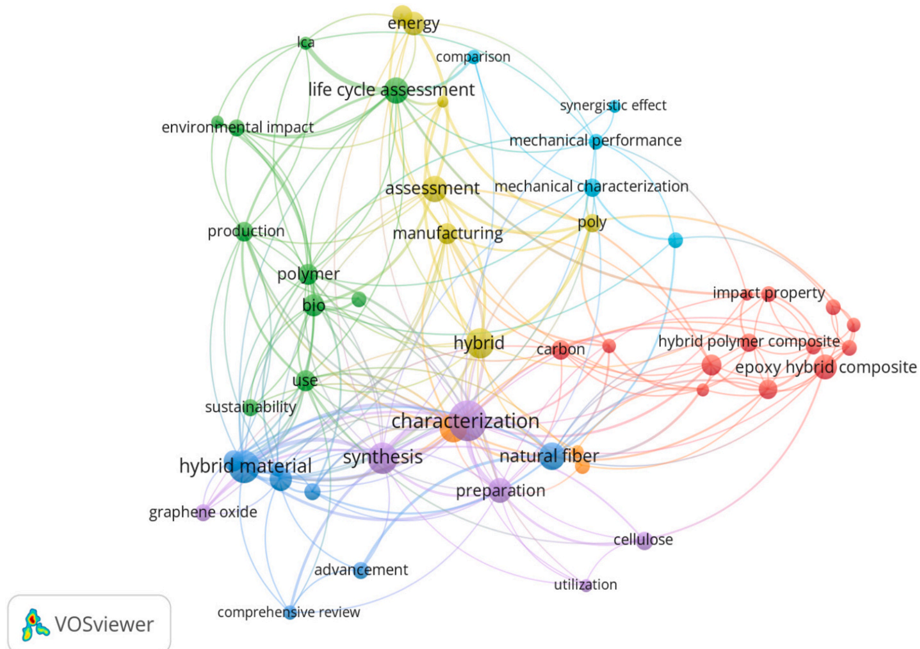

Fig. 2. Graph showing the connections among the keywords from the different research works screened.

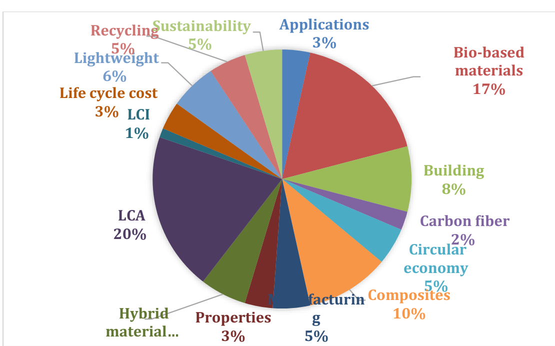

Fig. 3. Relevance of the different authors' keywords in the core papers of this review.

environmental footprint of the final material. In particular, as summarized in Table 2, the environmental impact load, which groups the six major environmental impacts, is reduced in approximately 2 % for the composites with 20 % wood flour, mainly related to a reduction in the photochemistry oxidation potential (PCOP) and a reduction of 1 % in acidification potential (AP) due to the incorporation of the SBS. Despite the modest modification of the footprint of the hybrid composite respect the untoughened PLA/wood composite and the lack of characterization of the final composite, authors consider them enough to prove the environmental benefits of such a hybrid material. Rodríguez et al. [5] obtained biocomposites using banana fibers, an agricultural residue, in up to 40 % loading in a matrix made of PLA and HDPE at different ratios. This interesting research work shows a ternary diagram with environmental, technical and economic performance in each side, thus allowing to determine the best combination for an intended application. To increase the environmental performance of the material, the content of banana fiber should be as high as possible, while if economic aspects are given more weight, fiber should not increase from 10 %. Total environmental footprint of composites is reduced about 40 % for the composites with 40 % of banana fibers, 30 % PLA and 30 % of HDPE, being this the option providing the lowest environmental impact while also keeping good technical performance. The highest reduction in impact is due to the lowering of resources consumption, due to the decrease in polymers use and to the introduction of a fiber coming from a waste.

Wegmann et al. [41] have recently analyzed the environmental behavior of a bonnet for a diesel engine vehicle, comparing the impacts of conventional metallic parts (either aluminum or steel, virgin, partially or fully recycled) with a hybrid composite one, including the reduction in fuel consumption for 300.000 km, due to the lightweighting. The hybrid composite studied, consisting of hybridized fibers (glass fibers coated with polycarbonate), provided the lowest environmental impact, mainly due to the reduction of energy consumption during the forming stage. These authors point-out the use of recycled components to obtain this composite as a strategy to continue improving the environmental performance of such parts, and propose the use of PA6 old fishing nets, glass fiber textiles products or bio-based precursors for carbon fibers obtaining as suitable options to achieve this. The composite provided better results in all environmental categories, except in resources depletion, which is favorable to the part made with 100 % or 70 % recycled aluminum. Similarly, Akhshik et al. [6,7] performed a comparative analysis of a conventional engine cover made of glass fiber (10 %) and polyamide (partially from recycled origin), and a new hybrid one, obtained with virgin polypropylene, cellulose and carbon fibers (20 and 10 %, respectively). The first observation made in these papers is that a weight reduction of 25 % can be achieved with this new proposal, with the part achieving requirements; these lightweighting directly impacts the performance of the part along its lifecycle, due to the reduction in fuel consumption. Once completed the LCA, these authors found considerable reductions in all categories analyzed, in terms of resources consumption, from energy consumption or waste produced; only water was found to be increased, with the hybrid composite requiring almost twice as much water as the current part. However, all categories of impacts were reduced, in over 50 % for GWP or human toxicity, and 80 % for eutrophication, to name only some of them.

La Rosa et al. [15] proposed the combination of glass and hemp fiber mats in a vinyl ester matrix, comparing the environmental impact of a model part (an elbow fitting for a water pipe), considering that a previous work determined that the mechanical properties of such hybrid composite were good enough for that application. The substitution of part of the glass fiber mat by the hemp one reduced in a 25 % the impact on human health, 17 % in ecosystems quality, and about 20 % in global

Table 3
Summary of results of LCA of different hybrid composites.

Matrix	Filler / reinforcement	Ratio*	Functional unit	Performance	Environmental benefits	Ref.
PLA PLA + 5 % SBS	Wood fiber	20 %	1 ton of injection-molded pallets	Not evaluated	−1 % AP, −3 % PCOP (due to SBS introduction)	[40]
PA	Glass fiber	10 %	Engine cover	According to standards	−50 % GWP, − 50 % HTP, −80 % EP (hybrid vs. glass composite)	[6]
PP	Cellulose/ carbon fiber	20 %/ 10 %				
PLA/ HDPE	Banana fiber	40 %	1 bottle lid (13.44 g of material)	+18 % tensile strength	−40 % overall impact	[5]
Vinyl ester	Glass mat	25 %	1 elbow fitting for refrigeration pipe	Reduced mechanical properties, but suitable for the intended application. −20 % weight	−20 % GWP, −18 % energy consumption, −50 % ODP, −20 HTP, −50 % EP (due to hemp incorporation)	[15]
	Glass-hemp mats	6.7 % glass/ 7 % hemp				
Epoxy	Glass-Jute mats	40 % glass/ 37 % jute (volume)	Sheets 1 × 1 m^2, 4.4 mm thick	Comparable tensile strength to pure epoxy, + 60 % in stiffness, + 100 % in bending properties, compared to jute composite	−60 % GWP, −90 % ODP, −60 % EP (compared to glass composite)	[42]
PHB	Kenaf + palm oil fibers	35.7 %	Mass of composite to cover 1 m^2 of usable area (1120 g)	Not evaluated	−20 % GWP, − 90 % HTP, + 500 % ODP (biocomposite vs. glass composites)	[43]
PP	Glass fiber					
PE	Glass fiber					

* Weight percentages, unless otherwise stated.

warming potential, although with a significant increase in agricultural land occupation. Pandita and collaborators [42] followed a similar approach, using an epoxy resin as matrix, and also placing the jute in the core. The increase in mechanical properties found with the incorporation of the glass fiber external layers also result in an increase in environmental impact, namely in GWP, eutrophication and acidification potentials. A comparative assessment of the hybrid composite with the jute fiber one, or with the neat resin was not conducted in this work, and so the conclusions are not complete. Besides, it is unclear whether the ratios of mats used in the hybrid composites refer to the composite or to the external layers or core.

Khoshnava et al. [43] have prepared a composite mixing a biomatrix (polyhydroxybutyrate, PHB) with two natural fibers: kenaf and oil palm fibers, pultruded into mats. The composites were prepared with two layers of the oil palm fibers, three of kenaf, and six of PHB. The mats were silanized to improve adhesion with the polymer. The results were compared with a multilayered composite containing a glass fiber mat and a polypropylene (PP) or polyethylene (PE) matrix. Both composites with glass fibers provided a similar environmental behavior, with the biocomposite providing a noticeable improvement in all parameters analyzed, except for ozone depletion (ODP), where the biocomposite shows 5 times more impact than oil-based/glass composites. Of particular significance are the differences found for human toxicity (HTP) and GWP. In general terms, after normalizing the impacts, a reduction of 33 % in the single score indicator was found for the biocomposites versus the PE/PP ones. In any case, this study does not include any characterization of the composites for the intended application (building material). A further study comparing the performance of such materials in terms of mechanical resistance, emissions, acoustic and thermal insulation, fire resistance, etc. would be needed before stating the better behavior of the biocomposite vs. the glass fiber ones, in order to ensure the new proposed composite accomplishes with required standards.

An important aspect that remains underexplored in the current body of literature is the adoption of a prospective LCA perspective, which is also a limitation of this review work. The studies analyzed in this systematic review do not provide any insight about technological maturation, future environmental regulations, or long-term market dynamics. This limitation restricts their applicability in forecasting the potential environmental performance of hybrid composites as they evolve. In this sense, the methodology proposed by Spreafico et al. (2023) [44], based on patent analysis, offers a novel pathway to anticipate the life cycle impacts of emerging eco-design solutions. As also stated by Padilla-Rivera et al. [45], the integration of Life Cycle Sustainability Assessment (LCSA) and Life Cycle Costing (LCC) methodologies should also be integrated in the overall analysis of the materials to help in informed decision-making for sustainable development. The review study presented here underscores the importance of incorporating economic evaluations alongside environmental assessments to provide a more comprehensive understanding of the sustainability of new materials and technologies. Future research in this field could benefit from integrating such foresight tools, enabling more robust environmental assessments under plausible future scenarios. The development of prospective LCA models could also help in aligning material innovations with sustainability transition pathways, an imperative especially relevant in rapidly evolving sectors like composites and bio-based materials.

4. Conclusions

The potential growth of hybrid materials is clear; the better properties achieved by the combination of two matrices or reinforcement/fillers allows for overcoming the limitations sometimes found in composites. The environmental aspects related to composites and, particularly, to biocomposites is not yet clear in the literature, although most authors highlight the benefits on the use of biobased materials, especially those coming from secondary processes or wastes, as a way to reduce the environmental footprint of materials. The increase in properties usually found for these materials and the reduction in weight of the matrix explain their generally improved environmental performance. However, deeper analysis is still needed, and each combination of materials has to be assessed individually, as there is a wide range of factors affecting the final calculations. When moving to hybrid materials, the existing literature is still very incipient, and the path has just only started to be walked. The limitations in the databases for certain materials and the difficulties in obtaining consistent data for the constituents of the final composite are hindering the environmental analysis of such materials.

Further efforts are then needed to make these data available. The analysis should also be performed in the basis of comparable units, if LCA is meant to be used as a tool to help in the materials selection process. Environmental performance should be included as a further property for materials, such as tensile modulus, elongation at break, or impact strength. In a micro-founded business economic prospective, all those performance indications can be useful and relevant for both internal control purpose and to properly enrich the system of financial and non-financial accountability statement and reporting activity under the SDG approach.

The few papers retrieved during this literature search not always are based on the same (or similar) functional units, limiting that way the comparisons between them, although it has been found that most authors refer to ReCiPe methods for the assessments.

In any case, it appears that the incorporation of natural fibers or biobased matrices contribute to significant reductions of the environmental footprint of composites, while keeping the parts functionality because of the combination of more than two different materials. Of particular interest are the composites containing waste streams (such as banana fibers) or those from crops with low fertilizers and pesticides requirements, such as hemp. Nevertheless, the situation is still unclear and further studies are required to obtain a clear understanding of the environmental benefits of such materials.

The studies found to date lack standardized functional units, consistent assumptions, and often omit critical technological context. Once these materials become more common, and more consistent data are available about them and their environmental performance, it would be of great relevance to incorporate a prospective vision in the LCA studies as future research. While the market offering of hybrid composites is rapidly expanding, most of the published studies do not include data or discussions related to manufacturing scalability, production costs, or market integration. This reflects a broader gap in connecting environmental performance with economic feasibility. Future work should also aim to incorporate LCC alongside LCA, and explore the intersection of technical performance, sustainability, and commercial viability to ensure the practical adoption of hybrid composites in industry.

Advancing the sustainability of hybrid polymer composites requires not only deeper environmental analysis but also stronger alignment with technological foresight and industrial viability. Bridging these elements is crucial to support meaningful innovation in line with sustainable development goals.

CRediT authorship contribution statement

Zaida Ortega: Methodology, Validation, Formal analysis, Funding acquisition, Writing – original draft, Supervision, Investigation, Conceptualization. **Agata Matarazzo:** Writing – original draft. **Luis Suárez:** Writing – original draft, Conceptualization, Formal analysis. **Pierluigi Catalfo:** Writing – original draft. **Carlo Ingrao:** Investigation, Writing – review & editing, Methodology, Formal analysis, Supervision, Conceptualization, Validation.

Declaration of competing interest

None.

Acknowledgments

Dr. Luis Suárez acknowledges the funding through the PhD grant program cofinanced by the Canarian Agency for Research, Innovation and Information Society of the Canary Islands Regional Council for Employment, Industry, Commerce and Knowledge (ACIISI) and by the European Social Fund (ESF) (Grant number TESIS2021010008).

Prof. Carlo Ingrao, as the corresponding author of this article, acknowledges that it has been published open access at no cost, thanks to the agreement between Italy and Elsevier, which the University of Bari Aldo Moro is part of.

Finally, the whole team of authors is grateful to the editors that have handled this article submission for their kind and prompt work; and, to the anonymous reviewers for their invaluable comments on the earlier version of this article.

Data availability

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

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