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Miscanthus-Derived Products for Material Applications: Can They Contribute to Greenhouse Gas Emission Mitigation?

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ABSTRACT

Miscanthus is a particularly promising lignocellulosic biomass as it can also grow under marginal conditions and can be used for a wide range of products including energy and material applications. The latter, including applications in the construction, textile, chemical, or agricultural sector, is becoming increasingly relevant today. In general, it is hypothesised that biobased products are advantageous in terms of their greenhouse gas (GHG) performance when compared to conventional—in particular fossil—alternatives. To investigate this, the life cycle assessment methodology is typically applied. However, assessments are subject to uncertainty and variability due to assumptions and methodological choices. Given the increasing interest in miscanthus-derived material applications, this study aims to draw more general conclusions about their GHG performance and relative mitigation potential. This should support a better understanding of their contribution to climate change mitigation objectives and guide the selection of promising products or product groups. A systematic review of peer-reviewed literature was conducted. In total, 20 studies reporting on 188 comparisons of the GHG performance of miscanthus-derived and alternative products were assessed. Most comparisons indicated potential GHG mitigation through miscanthus-derived products, with the majority ranging between 20% and 100% savings. Key parameters defining the relative performance include the selection of the reference product, consideration of soil carbon changes, changes in product and process design, as well as the incorporation of indirect Land Use Change (iLUC) impacts. Overall, we conclude that miscanthus-derived material applications have the potential to contribute to GHG emission mitigation if iLUC effects are minimised. Given the limited availability of agricultural land, miscanthus-derived products with high absolute GHG mitigation potential per unit of biomass used and long product lifetime are preferable. For future development, potential environmental trade-offs need to be monitored.

1 | Introduction

The European bioeconomy is positioned as a cornerstone of the European Union's climate neutrality strategy, which aims to achieve net-zero emissions by 2050 (European Union 2021). The substitution of conventional, often fossil resource-based products with innovative alternatives based on biomass is considered a key measure (European Union 2018a). Among potential biomass sources, the perennial crop miscanthus is particularly promising. The plant has a high biomass production potential, grows in a wide range of conditions, including marginal sites, and sequesters substantial amounts of carbon (Clifton-Brown et al. 2017; von Cossel et al. 2020; Lewandowski et al. 2016). As a lignocellulosic crop, miscanthus can be used in a wide range of biomass-to-product pathways (see for instance (Wagner et al. 2017)). Examples include the use of miscanthus in the energy sector for heat and power generation but also in the production of lignocellulosic ethanol. In the European Union (EU), the large-scale use of biomass in the power and transport sector has been at the center of attention for many years, as it has been strongly incentivized by policies and mandates (for instance the Renewable Energy Directive II (European Union 2018b)).

In recent times, the extension of electrification through technological development (e.g., improved battery technology, lower costs of renewable energy) has contributed to the availability of more cost- and GHG-effective solutions in the power and transportation sectors. For instance, electric heat pumps are increasingly replacing biomass use in low-temperature applications (Material Economics Sverige AB 2021), while electric vehicles outcompete conventional combustion engines on a cost and GHG basis (Bekel and Pauliuk 2019). Although these are essential steps in reducing GHG emissions from the power and transportation sector, both sectors are still far from being decarbonized. Nevertheless, these developments mean that, in addition to biomass use for energy purposes, material use has become equally important in recent years. This includes material applications in the construction (e.g., insulation materials), textile, chemical (plastics and platform chemicals), and agricultural sectors (e.g., soil amendments) (Material Economics Sverige AB 2021).

In line with the pivotal role of the bioeconomy in the EU's climate neutrality strategy, it is important to ensure that the application of biomass—irrespective of the sector—contributes to GHG mitigation. The life cycle assessment (LCA) methodology is typically applied to examine the relative GHG emission reduction potential of a biobased solution in comparison with its conventional alternative (Talwar and Holden 2022). This can be done as part of comprehensive LCAs, covering several environmental impact categories, but also within GHG emission-only assessments (carbon footprint assessments). In general, biobased solutions are considered advantageous in terms of GHG performance when compared to conventional—in particular fossil—alternatives (from here on referred to as GHG favourability) (Zuiderveen et al. 2023). However, it should be considered that these assessments are typically subject to uncertainty and variability due to the conditions assumed in the respective study as well as methodological choices (Talwar and Holden 2022; Heijungs and Huijbregts 2004).

For lignocellulosic ethanol, a well-researched bio-based product that has been the subject of manifold LCA studies (e.g., (Cronin et al. 2017; Falano et al. 2014; Lask et al. 2019)), it has been shown that a number of key parameters can substantially influence GHG emissions over its life cycle. These include inter alia the setting of system boundaries, the choice of functional unit, allocation methods, and co-product handling, as well as in/exclusion of direct and indirect land use changes (Gerbrandt et al. 2016). These parameters are also likely to influence the life cycle GHG emissions of miscanthus-derived products for material applications, which might compromise the hypothesized GHG favourability of these solutions. In light of the growing interest in material applications of miscanthus, this requires further assessment.

This study aims to inform the increasing number of stakeholders interested in miscanthus-derived material applications on their GHG favourability, their robustness, and possible issues in GHG emission assessments. Ideally, this should support a better understanding of the contribution of miscanthus-derived solutions to climate change mitigation and guide the selection of promising products or product groups. This study focuses primarily on GHG emission assessment-related aspects, as it is directly motivated by the EU's climate change mitigation goals.

For this purpose, a systematic review of peer-reviewed literature on miscanthus-derived products for material applications was conducted. Based on information from this literature review, the relative mitigation potential of miscanthus-derived material applications is assessed. In addition, the robustness of the mitigation potentials considering methodological and technical parameters is discussed.

2 | Material and Methods

2.1 | Review Procedure—Identification of Relevant Studies

A systematic review of LCA literature was conducted following the approach outlined in Zumsteg et al. (2012), who introduced an LCA-specific literature review methodology. In line with the approach suggested therein, the structure of the present review can be defined by referring to the PIFT (Product/Process, Impacts, Flows, Types of LCAs) framework. The corresponding information is presented in Table 1.

Against the background of this structure, relevant literature was searched for in a systematic procedure as detailed in Figure 1. Studies were identified by means of a keyword-based literature database search in Scopus. Keywords were selected to reflect (1) the use of miscanthus in the applications and (2) the domain of life cycle GHG assessments. Accordingly, the term for the database search was defined as "miscanthus AND ("sustainability assessment" OR "Life cycle analysis" OR "Life cycle assessment" OR lcsa OR lca OR "carbon footprint" OR "greenhouse gas emission" OR "GHG emission")". Using this term, 309 records were identified in the Scopus database.

TABLE 1 | Structure of the literature review, as suggested by Zumsteg et al. (2012).

P: Product or process	I: Impact of interest	F: Flows or economic sectors included	T: Type(s) of life cycle assessment
Miscanthus-derived products for material applications	Global warming potential/ Climate change	Construction materials, chemicals, plastics/ composites, etc.	Peer-reviewed, comparative LCAs (regardless if process-based, input–output or hybrid)

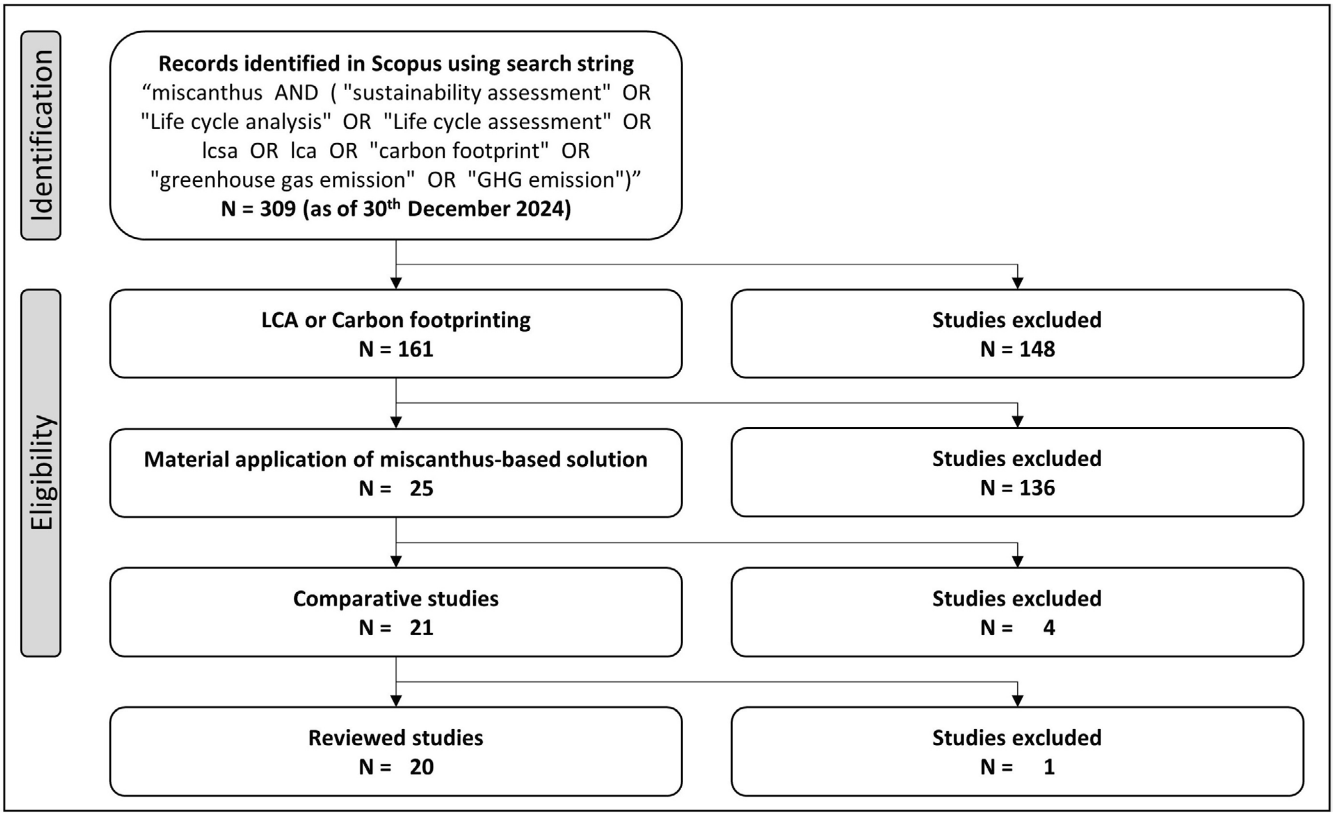

FIGURE 1 | Methodological procedure of the systematic literature review (in line with Zumsteg et al. 2012).

The initial set of records was subjected to a relevance check. Only those studies were included that conducted LCAs, i.e., evaluated GHG emissions and/or global warming potential (GWP) over the life cycle of a product or service. Studies that merely examined or measured direct GHG emissions, and reviews were excluded. This step resulted in the exclusion of 148 studies.

In the following step, studies were classified according to the areas in which the assessments were conducted. Three categories were distinguished: agricultural (miscanthus cultivation), energy (e.g., combustion for heat and power generation as well as ethanol for use in transportation), and material applications (insulation materials, chemicals, etc.). Only studies reporting on material applications were considered eligible in line with the review criteria. This resulted in the exclusion of 136 studies examining energy applications and miscanthus cultivation only (for examples see Table S1).

Of the remaining studies, four were non-comparative, that is, did not report impacts of a reference product and were thus excluded. Overall, 21 published studies met the eligibility criteria. Due to an incomprehensive description of the methodological approach, one of the remaining studies (Witzleben 2022) was excluded from further analysis, resulting in 20 published studies making up the final review dataset.

2.2 | Information Extracted From Relevant Studies

The studies included in the final review dataset were thoroughly scrutinised, and a wide range of information was extracted from the main texts and Supporting Information. This includes results of the studies and covers methodological aspects and key inventory parameters that potentially influence the life cycle GHG emissions of miscanthus-derived products for material applications. An overview of the data extracted from each study included is presented in Table 2.

The information provided in the studies was also used to derive additional indicators. This includes, for instance, the relative GHG mitigation potential, which was extracted from result tables and figures (see Table 2 for the calculation approach), as well as a proxy for the quantity of GHG emissions of the miscanthus cultivation. The latter was derived by drawing on details of the miscanthus cultivation system as given in the respective study and a simple model for the calculation of the GHG emissions associated with miscanthus cultivation (as described in Lask, Kam, et al. (2021)). This approach was taken for all studies to derive comparable estimates of the GHG emissions related to the miscanthus cultivation. A comprehensive overview of all the information collated is available in Table S2.

3 | Results

3.1 | Overview and Description of Relevant Studies

The 20 studies identified as relevant were published between 2008 and 2024. Three were based in Canada, one in the US, and one in China. The remaining studies were based in Europe, focusing mainly on Germany. Table 3 presents an overview of the studies, providing associated key information.

TABLE 2 | Overview of information extracted from relevant studies.

Phase	Item	Description
Goal and Scope	Miscanthus-derived products	For example, insulation material
	Reference product/process to which miscanthus-derived product is compared	For example, mineral wool, etc.
	System boundaries	Cradle-to-gate or cradle-to-grave
	Geographical reference	For example, Germany, China, etc.
	Functional unit	For example, 1 kg of HMF, insulating 1 m2 of external wall of a residential building with 0.24 W m−2 K−1 for 70 years
	LCI modelling approach	Attributional or consequential
	Handling of multifunctional activities	Allocation or substitution
Inventory	Agricultural activities	
	Main data source	Field data, literature or simulation
	Key parameters	For example, cultivation period, yield, fertiliser application, soil carbon changes
	Greenhouse gas intensity	Estimated based on (Lask, Kam, et al. 2021)
	Conversion activities	
	Main data source of conversion activities	Lab data, literature or simulation
	Major source of process energy	Non-renewable, renewable or mix
	End-of-life	For example, incineration, composting, etc.
	Background data	
	Main source	For example, ecoinvent, GaBi, etc.
Impact assessment	Consideration of impacts beyond global warming potential	Yes or No
	If applicable, LCIA method collection used	For example, ReCiPe 2016, TRACI v2.2, etc.
	If applicable, trade-offs with other environmental impact categories	Yes or No—which categories
	GHG emissions per functional unit of miscanthus-derived product and conv. reference	
	Relative GHG emission mitigation potential of miscanthus-derived product	Calculated as Relative saving (in %) $= \frac{(GHG_{reference} - GHG_{miscanthus})}{GHG_{reference}}$
	If available, information on sensitivity considerations	For example, parameter variation and scenario analysis considered (incl. iLUC)
	If available, GHG emission saving rel. to conv. reference given sensitivity analysis considerations	
	Contribution of miscanthus cultivation to total GWP impacts per FU	For example, 32%

In total, the included studies assessed 35 miscanthus-based applications and variations thereof (see Table 3). Overall, mainly four economic sectors were covered:

- The construction sector with products such as insulation material (e.g., Schulte et al. (2021)), miscanthus-lime blocks for wall assemblies (Ntimugura et al. (2021)) and oriented strand boards (Liao et al. (2021)).
- The chemical sector covering miscanthus-derived solutions for plastics (e.g., Ni et al. (2021)) and composite applications (e.g., Roy, Defersha, et al. 2020) as well as for the production of platform chemicals (e.g., Götz et al. (2023)).
- The agricultural sector including miscanthus usage as soil amendment (Roy, Dutta, and Gallant 2020) and as substrate in horticulture (Ruett et al. 2024).

TABLE 3 | Overview and details of the selected studies; ordered according to application class.

	ID | Comp	Product		System (cradle-to-...)	LCI modelling approach	Geographical boundaries	Uncertainty considered	References (ID)
		Miscanthus-derived	References					
Building—Insulation materials	1.1.1	Insulation material	Expanded polystyrene	Grave	Attributional	GER	Biomass Yield	(Schulte et al. 2021) (1)
	1.1.2		Stone wool					
	1.1.3		Wood fiber					
	1.1.4		Hemp fiber					
	1.1.5		Flax					
	2.1.1	Insulation material	Glass wool	Grave	Attributional	GBR, TUR, RUS, UKR, GER, NED	Biomass Yield	(Wagner et al. 2017) (2)
	3.1.1	Insulation material	Glass wool	Grave	Attributional	SWE, DEN, GER, ENG	Biomass Yield	(Meyer et al. 2017) (3)
	4.1.1	Insulation material	Mineral wool	Grave	Attributional	GER	Process design	(Uihlein et al. 2008) (4)
Building—Others	5.1.1	Non-load bearing concrete block	Light clay brick	Grave	Attributional	FRA	Biomass yield, dLUC, iLUC	(Jury et al. 2022) (5)
	5.2.1	Load bearing concrete block	Conventional concrete block					
	6.1.1	Oriented Strand Boards	Conventional oriented strand boards	Gate	Attributional	CHN	Product & Process design	(Liao et al. 2021) (6)
	7.1.1	Timber-framed wall with miscanthus concrete	Standard solid wall with mineral wool	Grave	Attributional	GBR	(Product design, transport dist.)	(Ntimugura et al. 2021) (7)
	7.2.1	Insulation-replacing miscanthus concrete		Grave	Attributional	GBR		
Composites—Fibers and fillers	8.1.1	Miscanthus fibre reinforced cellulose acetate	Glass fibre reinforced polypropylene	Gate	Attributional	GER	Product &Process design	(Liu et al. 2024) (8)
	9.1.1	Polypropylene reinforced with biocarbon and Miscanthus fiber	Talc-reinforced polypropylene composite	Grave	Attributional	CAN	Energy consumption, Transport dist., fuel use in use-phase	(Roy, Defersha, et al. 2020) (9)
	10.1.1	Polypropylene composite reinforced with miscanthus biochar	Talc-reinforced polypropylene composite	Grave	Attributional	CAN	Transport mode & distance	(Tadele et al. 2020) (10)

(Continues)

TABLE 3 | (Continued)

	ID | Comp	Product		System (cradle-to-...)	LCI modelling approach	Geographical boundaries	Uncertainty considered	References (ID)
		Miscanthus-derived	References					
Plastics and platform chemicals	11.1.1	Hydroxymethylfurfural (HMF)	Maize-based HMF	Gate	Attributional	GER	Biomass yield, Process design	(Götz et al. 2023) (11)
	12.1.1	Polyethylene terephtalate (PET)—30% biobased	Fossil PET	Gate	Hybrid	Europe	None	(García-Velásquez and van der Meer 2022) (12)
	12.1.2		PET—sugarcane—30% bio-based/70% fossil					
	12.1.3		PET—sugarcane—30% bio-based/70% fossil					
	12.1.4		PET—sugarcane molasse—30% bio-based/70% fossil					
	12.1.5		PET—sugar beet—30% bio-based/70% fossil					
	12.1.6		PET—wheat—30% bio-based/70% fossil					
	12.2.1	Polyethylene terephtalate (PET)—100% biobased	PET—fossil	Gate	Hybrid	Europe		
	12.2.2		PET—sugarcane—100% bio-based					
	12.2.3		PET—sugarcane—100% bio-based					
	12.2.4		PET—sugarcane molasse—100% bio-based					
	12.2.5		PET—sugar beet—100% bio-based					
	12.2.6		PET—wheat—100% bio-based					
	13.1.1	Purified terephtalic acid (PTA)	PTA—fossil	Gate	Attributional	NLD	General uncertainty via Pedigree	(Gian et al. 2022) (13)

(Continues)

TABLE 3 | (Continued)

	ID | Comp	Product		System (cradle-to-...)	LCI modelling approach	Geographical boundaries	Uncertainty considered	References (ID)
		Miscanthus-derived	**References**					
Plastics and platform chemicals	14.1.1	Polybutylene succinate plastic	Polypropylene—fossil	Grave	Consequential	GBR	None	(Ni et al. 2021) (14)
			Polyethylene terephtalate—fossil					
			Polybutylene succinate—maize grain					
	15.1.1	Polybutylene succinate (PBS)—based products	Polypropylene—fossil	Grave	Attributional	Europe	None	(Patel et al. 2018) (15)
	16.1.1	Propanediol	1,3-PDO—fossil	Grave	Consequential	Mediterranean	Process design	(Schmidt et al. 2015) (16)
	17.1.1	Polylactic acd	Polyethylene terephthalate—fossil	Gate	Consequential	NED	Process design	(Bos et al. 2012) (17)
	17.1.2		Polylactic acid—maize starch					
	17.1.3		Polylactic acid—wheat starch					
	17.1.4		Polylactic acid—sugar beet					
	17.1.5		Polylactic acid—sugar cane					
	17.2.1	Polyethylene	LDPE—fossil					
	17.2.2		Polyethylene—maize starch					
	17.2.3		Polyethylene—wheat starch					
	17.2.4		Polyethylene—sugar beet					
	17.2.5		Polyethylene—sugar cane					
Agri–/horticultural	18.1.1	Hydrochar as soil amendment	Peat moss hydrothermally carbonized	Grave	Attributional	CAN	Decomposition, transport distance	(Roy, Dutta, and Gallant 2020) (18)
	19.1.1	Horticultural substrate	Peat	Grave	Attributional	GER	Single/Cascading & biochar addition	(Ruett et al. 2024) (19)
	19.1.2		Stone wool					
	19.1.3		Coconut coir					

(Continues)

TABLE 3 | (Continued)

	ID | Comp	Product: Miscanthus-derived	Product: References	System (cradle-to-...)	LCI modelling approach	Geographical boundaries	Uncertainty considered	References (ID)
Others	20.1.1	Carboxylated cellulose nanocrystals (CNC) for graphene exfoliation	Sodium Deoxycholate	Gate	Attributional	USA	None	(Hui et al. 2024) (20)
	20.1.2		Triton X-100					
	20.1.3		Sodium Cholate					
	20.1.4		Ethyl Cellulose + Ethanol					
	20.1.5		Cyrene					
	20.1.6		Cyrene					

- And lastly, graphene production for which Hui et al. (2024) assessed the usage of miscanthus-derived carboxylated cellulose nanocrystals.

Each of these studies compared the miscanthus-derived product to at least one non-miscanthus-derived reference product. Ten studies (1, 5, 7, 8, 12, 13, 14, 17, 19, 20) did examine either more than one miscanthus-derived product or reference product.

As opposed to LCAs and carbon footprint studies conducted in business contexts, the studies included were set in scientific contexts, responding to specific research goals and objectives. Thus, they did not apply harmonised modelling frameworks as suggested, for instance, in product category rules for environmental product declarations (for an overview and related challenges, see Konradsen et al. 2024). Substantial variation was encountered in the setup of the reviewed studies. This includes aspects such as system boundary definition, LCI modelling, handling of multifunctional activities, use of LCI databases, and handling of uncertainty.

The majority of studies defined **system boundaries** as cradle-to-grave, including use and end-of-life (EOL). Seven studies excluded impacts beyond the production phase (cradle-to-gate), stating similar environmental characteristics of these phases for the miscanthus-derived product systems and the reference system. With respect to **LCI modelling**, 16 studies were categorised as attributional approaches (not explicitly stated in eight cases and thus classified by the authors of this study in accordance with (ILCD 2010)). Three were of consequential nature, being intended forpolicysupport(Bosetal.2012)oranalysisofmacro-leveldecisions (Ni et al. 2021; Schmidt et al. 2015). In addition, García-Velásquez and van der Meer (2022) classified their approach as hybrid.

Handling of multifunctional activities and processes in the foreground system is a key procedure when conducting LCAs. Typically, allocation (based on physical or economic measures) and substitution are used. Among the reviewed studies, allocation was applied in six, substitution in seven, and a combination in four. Allocation based on economic values was applied in three studies (Schulte et al. 2021; Götz et al. 2023; Ni et al. 2021). Physical relations, namely energy and mass, were used in one (Roy, Defersha, et al. 2020) and two (Liu et al. 2024; Tadele et al. 2020) studies, respectively. In three studies, no multifunctionality issues needed to be solved in the miscanthus-derived product system (Liao et al. 2021; Meyer et al. 2017; Hui et al. 2024). LCAs rely heavily on **LCI databases** such as ecoinvent (Wernet et al. 2016) and GaBi/Sphera MLC to account for impacts associated with the background system. Of the studies reviewed, 11 draw on information from ecoinvent, with two studies (Wagner et al. 2017; Götz et al. 2023) specifying the selected system model as cut-off. The remaining studies used other databases (e.g., GaBi) or did not specify their source (see Table S2).

All selected studies performed at least one type of uncertainty assessment. Most typically, biomass yields and transportation distances were tested to assess the effect on the overall result. In addition, conversion process parameters such as conversion efficiency and co-product amounts were varied. Scenario analyses include variation in end-of-life scenarios (incineration vs. composting, incineration with/without energy recovery), processing pathways (organosolv vs. steam explosion), and change of background datasets (e.g., rail replacing road transport and renewable electricity usage).

Overall, this compilation of modelling parameters highlights the fact that the studies are built on substantially different fundaments. Thus, absolute figures on GHG impacts cannot be used to draw conclusions based on comparisons between studies. For this reason, the present study builds on the study-specific relative GHG emission saving of miscanthus-derived products relative to the alternative reference product (see Table 2 for how it was calculated). For this, each comparison of a miscanthus- and non-miscanthus-derived product was considered an observation and the relative GHG emission saving of the miscanthus solutions was derived. Also, results of uncertainty analyses were considered. Overall, this resulted in 188 observations that were identified in the reviewed literature (see Supporting Information for a comprehensive overview). This approach was taken to draw more general conclusions regarding the comparative performance of miscanthus-derived products and their conventional references.

3.2 | Relative GHG Mitigation Potential as Indicated in Studies

188 observations of comparisons between miscanthus-derived products and reference products were identified (including fossil- and biobased alternatives). For each comparison, the relative GHG mitigation potential is presented in Figure 2, where a positive percentage indicates lower greenhouse gas emissions, and thus an advantageous performance (GHG favourability) of the miscanthus-derived product.

Overall, potential GHG mitigation through miscanthus-derived products was reported for most of the observations. For **miscanthus-derived insulation**, GHG mitigation potentials were reported for most cases.

Schulte et al. (2021) (observations 1.1.1 and 1.1.2) reported substantial GHG reduction potentials of miscanthus-derived insulation material in comparison with conventional reference products (expanded polystyrene and stone wool). This is in line with other studies on miscanthus-derived insulation products (Wagner et al. 2017; Meyer et al. 2017), for which mitigation potentials between 69% and 101% were reported (2.1.1 and 3.1.1). In contrast, Uihlein et al. (2008) found miscanthus-based insulation material to perform worse than the conventional, fossil-based reference product (4.1.1). For bio-based reference products such as hemp- and flax-based insulation materials, Schulte et al. (2021) found mitigation potentials between 73% and 81% (1.1.4 and 1.1.5). In contrast, for comparisons with wood-based insulation material, slightly higher GHG emissions (between 2% and −25%) per functional unit were observed for the miscanthus-derived materials (1.1.3).

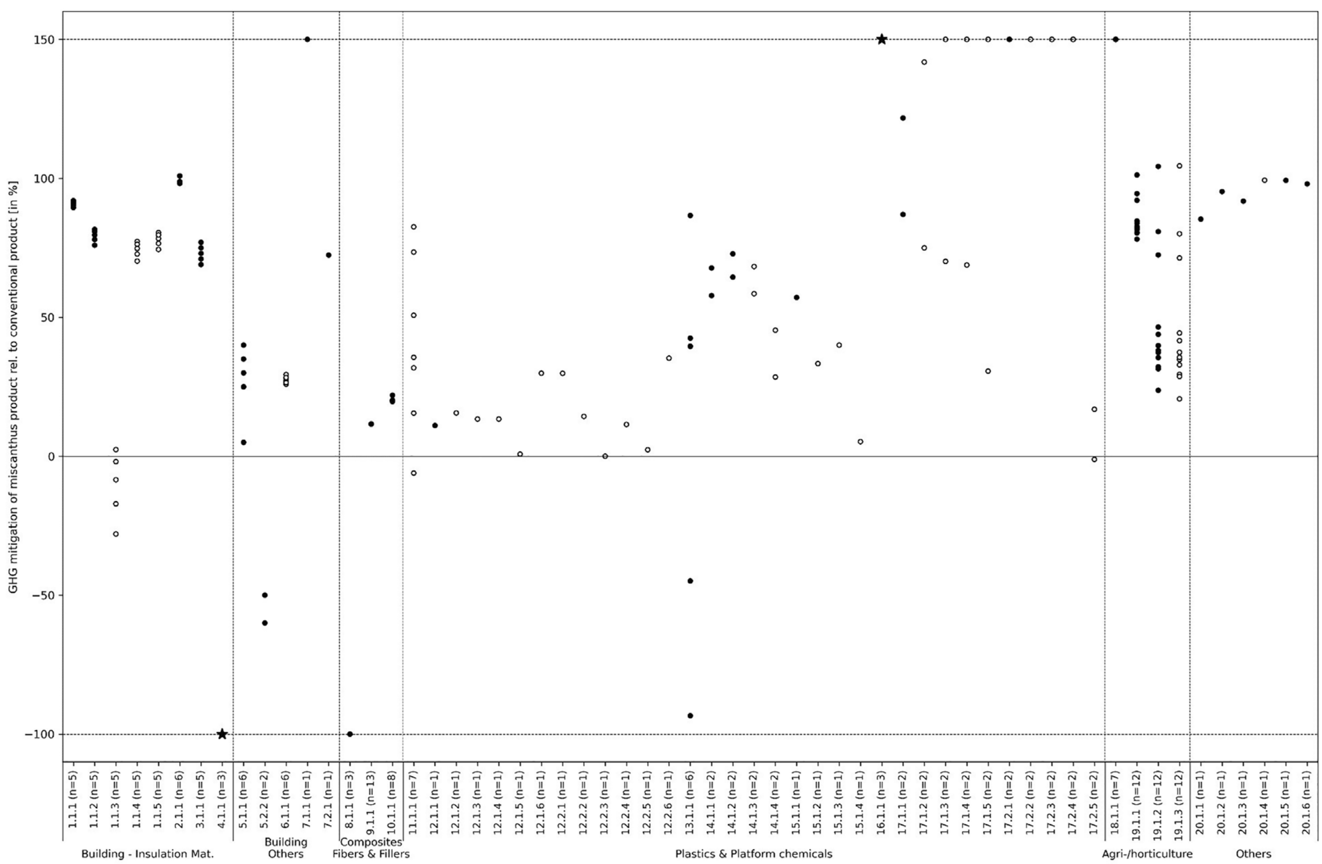

FIGURE 2 | Relative greenhouse gas (GHG) mitigation potential of miscanthus-derived products relative to reference products (comparisons with fossil or mineral reference products indicated by ●; bio-based ones by ○). Rel. GHG mitigation potentials could not be calculated for 4.1.1 and 16.1.1; only an indication is depicted (★). For better readability, mitigation potentials above 150% and below −150% were cut-off and presented as 150% and −100%, respectively. This applies to 8.1.1, 18.1, partially 17.1 and 17.2, as well as 18.1.1.

For **applications in the building sector other than insulation material**, a mitigation potential of 26% was found for miscanthus-derived oriented strand boards (vs. wood-based alternative) (Liao et al. 2021) (6.1.1) as well as 72% and 186% for miscanthus concrete usage in wall assemblies (Ntimugura et al. 2021) (7.1.1 and 7.2.1). Jury et al. (2022) assessed the use of miscanthus-concrete in two separate setups as well. They found the non-load-bearing setup (5.1.1) having GHG mitigation potentials of up to 40%, while the load-bearing setup performed worse than the conventional reference setup (5.2.2).

Observations on **miscanthus-derived filler and fibre products for composite products** displayed a mixed trend: Two studies showed GHG mitigation potentials ranging between 12% and 22%. This includes fossil polypropylene filled with miscanthus-derived biochar and reinforced with miscanthus fibres (Roy, Dutta, and Gallant 2020; Tadele et al. 2020) (9.1.1 and 10.1.1). In contrast, Liu et al. (2024) 8.1.1 did not observe GHG mitigation potentials for a composite incorporating miscanthus fibres in cellulose acetate.

Mitigation potentials of **miscanthus-derived plastics and platform chemicals** varied substantially, ranging from −93% (Gian et al. 2022) (13.1.1) to 1973% (Bos et al. 2012) (17.2.3), with most of the observations reporting reduction potentials between 10% and 80% for the miscanthus-derived products. Schmidt et al. (2015) (16.1.1) found that the production of **platform chemicals** from miscanthus tends to result in fewer GHG emissions than the production of conventional reference products. However, the positive GHG mitigation potential observed was sensitive to biomass conversion parameters as shown in the uncertainty analyses of the study. From Götz et al. (2023, 11.1.1) and Gian et al. (2022, 13.1.1), it was shown that the GHG favourability of the miscanthus-derived products is sensitive to a set of assumptions. For PTA production (Gian et al. 2022) (13.1.1), the selection of the processing pathway—being either fermentative or thermochemical—determined the outcome of the comparison. For HMF production (Götz et al. 2023), the outcome of the comparison was sensitive to the assumed miscanthus yield as well as the processing setup (with or without lignin upgrading) (11.1.1).

Two studies assessed the use of miscanthus in **agri/horticultural applications**. Roy, Dutta, and Gallant (2020) (18.1.1) analyzed the use of miscanthus-derived hydrochar as a soil amendment and found that in comparison with the use of peat moss-derived hydrochar, a substantial GHG mitigation potential of 1144% could be achieved (for reasons of readability, not shown in Figure 2). Ruett et al. (2024) assessed the application of miscanthus as soil substrate, identifying substantial GHG mitigation potentials in comparison with peat (19.1.1), stone wool (19.1.2), and coconut coir (19.1.3). Substantial variation in the GHG mitigation potential was observed, as a number of scenarios were considered: First, the addition of miscanthus-derived biochar was considered, and it was shown that the addition of biochar tends to result in substantial GHG reduction potentials (see Table S2). Second, the re-use of substrate was assessed, indicating that re-using substrate is beneficial in terms of GHG mitigation. Overall, and irrespective of the setup, substantially higher potential savings of the miscanthus-based settings were observed for comparisons with peat than when compared with glass wool or coconut coir.

Complementing these previous applications, Hui et al. (2024) assessed graphene production by means of miscanthus-derived Carboxylated Cellulose Nanocrystals (CNC) and compared the potential GHG emissions with those of other standard approaches. Their study found that the miscanthus-supported graphene production results in substantial GHG mitigation potentials between 85% and 99% in comparison to standard approaches (20.1.1–20.1.6).

4 | Discussion

The majority of observations found that miscanthus-derived products result in less GHG emissions than their conventional counterparts. However, the question remains how robust the observed relative GHG favourability of miscanthus-derived products is, that is, whether miscanthus-based products are favourable in terms of the life-cycle GHG emissions in comparison with conventional products; even after accounting for potential variation in individual parameters in the life-cycle GHG assessment. In addition, potential implications for the further development of miscanthus-derived material applications need to be discussed.

4.1 | Robustness of Miscanthus-Derived Products′ Favourability

This section is structured along the product life cycle phases, starting with aspects related to biomass cultivation. This is followed by aspects related to conversion, use phase as well as EOL. Finally, overarching aspects are examined.

4.1.1 | Miscanthus Cultivation

The GHG intensity of agricultural products can vary substantially given the differences in management and geographical bio-physical conditions (Goglio et al. 2015; Miller et al. 2006). Key parameters for the calculation of life cycle GHG emissions of miscanthus cultivation are the duration of the cultivation period, dry matter (DM) yield, amounts of nitrogen and potassium fertiliser applied, as well as the transportation distance of the biomass (Lask, Rukavina, et al. 2021). In addition, the magnitude of soil carbon changes can substantially influence the GHG balance of the cultivation phase (Lask et al. 2019; Ledo et al. 2018; Robertson et al. 2017).

The studies considered in this review did not show general correlations between cultivation system setup and geographical factors, preventing any further conclusion regarding the relationship between geography and GHG favourability. Overall, required inventory information was mainly derived from literature and field data. Typically, a cultivation period of 20 years (15 years in 3 studies) and yields ranging between 8.4 and 18.4 t DM ha^{-1} were assumed. Where fertilisation of the miscanthus cultivation was assumed (16 out of 20 studies), schemes differed mainly with regard to the nitrogen application rate, which ranged between 0 and 60 kg N ha^{-1} $year^{-1}$. The variation for potassium was less pronounced, with application rates ranging between 100 and 120 kg K_2O ha^{-1}. For the biomass transportation distances, the included studies assumed a broad range of values between 20 and 400 km. The GHG emission intensity of the cultivation systems was estimated to vary by a factor of three (ranging from 64 to 196 g CO_2eq (kg DM)$^{-1}$, Table S2) due to the described fluctuation of the abovementioned parameters. Relatively higher emissions were encountered in studies that assumed fertilisation-intensive systems. In commercial practice, nitrogen fertilisation is usually minimal—often even inexistent—as atmospheric nitrogen deposition can counterbalance removal from biomass (McCalmont et al. 2017). If future miscanthus-derived products for material application are introduced on the market, miscanthus production would be required at scale and would likely reflect today's commercial cultivation conditions without (or with low maximum levels of) nitrogen fertilisers. Miscanthus cultivation emissions per unit of biomass can thus be expected in the lower range of the values given above.

For most observations, biomass cultivation is only a minor contributor to the life cycle GHG in comparison with the impacts from the processing/conversion stage (exceptions are Ntimugura et al. (2021) and Schulte et al. (2021) with contributions of 32% and 47%, respectively). Nevertheless, it was shown, for example, by Götz et al. (2023) that assumptions regarding the yield can influence the observed GHG emission favourability. Nevertheless, the observed GHG emission favourability of most of the miscanthus-derived products can be considered robust with respect to potential variations in the cultivation systems. The increasing consideration of commercial, low-fertiliser input cultivation in LCAs and carbon footprint studies should further corroborate the observed favourability of miscanthus-derived products. This conclusion is further strengthened by considering the substantial potential for soil carbon sequestration through miscanthus cultivation, which is often not accounted for due to lacking consistency in methodologies. This is evidenced by the present set of selected studies, of which only three took soil carbon changes into account (Ni et al. (2021), Roy, Dutta, and Gallant (2020), and Götz et al. (2023)). If included, these considerations could substantially reduce the GWP impact of miscanthus-derived products and thus improve the robustness of their GHG favourability.

4.1.2 | Conversion

Modelling of the biomass conversion stage in the considered studies relied predominantly on literature information. Five studies derived required inventory information (at least partially) from lab-scale experiments. Götz et al. (2023) set up a process model using AspenPlus, detailing the production of Hydroxymethylfurfural (HMF) at a commercially viable scale. Assessments based on data from literature and laboratory experiments carry the risk of process conditions and product design not being representative for commercial scale operations.

The relevance of **product design** can be estimated by two examples: The first is the comparison of the GHG intensity of insulation material as presented in Wagner et al. (2017), Meyer et al. (2017), and Uihlein et al. (2008). A substantial reduction in GHG emissions (and thus an increase in the relative GHG mitigation potential) was observed when comparing the earlier study by Uihlein et al. (2008) with the newer studies from 2017 and 2018. This improvement mainly stems from a substantial reduction of polypropylene in the production of the insulation material, which was no longer required due to a different product design. Second, Ntimugura et al. (2021) showed that the overall GHG emissions of miscanthus-derived wall assemblies could be substantially reduced by reducing the amount of binder used in their production. Although the possible modification of the wall assemblies' mechanical properties was not considered in the study, this emphasizes the potential for optimization through product design.

Development and advancement of **process design** are also expected to further improve the climate change performance of miscanthus-derived products. Gian et al. (2022) and Ni et al. (2021) showed that variation in the process setup, for instance pretreatment via steam explosion or organosolv as well as fermentative or thermochemical biomass processing, can substantially affect the overall GHG performance of miscanthus-derived products. This knowledge can be used to optimise process designs in the future. In addition, advancement in conversion efficiencies (as shown, for instance, in Bos et al. (2012)) and up-scaling of production facilities will further contribute to more efficient production processes (Zuiderveen et al. 2023). As these aspects are not incorporated in the studies included in this review, it is to be expected that climate change impacts of miscanthus-derived products will further decrease and thus increase the robustness of the GHG favourability shown in Figure 2. Innovative, emerging products are generally more likely to benefit from efficiency and optimisation gains in production processes and product design than incumbent reference products (Bergerson et al. 2020).

4.1.3 | Use Phase

When miscanthus biomass is used in material applications, the carbon assimilated by the plant is sequestered for the lifetime of the miscanthus-derived product. The accounting of this carbon storage is, however, much disputed due to its impermanence (Brandão et al. 2013; Butnar et al. 2024). Even a short-term delay of emissions could be a building block in preventing the immediate surpassing of climate tipping points (Jørgensen et al. 2015). None of the selected studies focusing on building, composite, and chemical (plastics and platform) applications, however, accounted for associated credits. As such, these studies apply a conservative approach that rather under- than overestimates the GHG favourability of miscanthus-derived products (at least in comparison with fossil-based reference products). Applications incorporating high amounts of miscanthus per functional unit and extensive use phase could particularly benefit. If Schulte et al. (2021), for instance, had credited the temporary storage of carbon in miscanthus-derived insulation material over the use phase as suggested in (ILCD 2010), the product's footprint would decrease from ~3 kg to ~−14 CO_2eq per functional unit, assuming an input of 14.15 kg miscanthus dry matter per functional unit and a use phase of 70 years with a miscanthus carbon content of 48%. Where the proportion of miscanthus in the final product was only minor, such as in miscanthus-reinforced composites, the influence on absolute GHG impact and relative mitigation potential was marginal. These examples highlight the fact that use-phase considerations are unlikely to diminish the robustness of the GHG favourability of miscanthus-derived products. This conclusion is further corroborated when including findings from studies on agri/horticultural applications where consideration of permanent carbon storage related to the use of miscanthus-derived biochar resulted in substantial GHG reduction potentials due to long-term stability of biochar in soil (Roy, Dutta, and Gallant 2020; Ruett et al. 2024).

4.1.4 | End-Of-Life (EOL)

For applications such as building materials, composites, and plastics, two major treatment pathways were typically considered—composting and incineration. With regard to the absolute amount of carbon released, the difference between both pathways is assumed to be marginal (clearly, fossil and biogenic carbon are to be distinguished). However, if heat from incinerations can be recovered, it is accounted for in most of the studies via substitution. Associated credits for the substitution of heat or electricity production can be substantial contributors in the life cycle of miscanthus-derived applications and can vary widely depending on geographical focus due to varying electricity sources (natural gas, hydropower, nuclear, etc.) (Wagner et al. 2017). In most studies, EOL pathways were selected uniformly for both miscanthus-derived products and the reference product. In these cases, the EOL phase most likely does not affect the robustness of the GHG favourability of miscanthus-derived products. In a few cases, however, the treatment pathways differed. For instance, stone and glass wool used in insulation material have to be disposed of in landfill, while the miscanthus-derived alternative was assumed to be incinerated (Schulte et al. 2021; Wagner et al. 2017). Here, credits associated with the EOL treatment are more relevant for the GHG favourability of the miscanthus-derived products. However, the contribution of the EOL credits was negligible in the studies considered in the present work. In addition, it is expected that their relevance will continue to decline. This is mainly due to a reduced GHG intensity of the substituted energy mix in line with the anticipated defossilisation of the energy sector (Vandepaer et al. 2020). Together, this points to the conclusion that the overall GHG favourability of miscanthus-derived products is likely to remain intact. This is further corroborated by Ni et al. (2021), who compared two EOL treatments for polybutylene succinate: incineration and composting. For both scenarios, a clear GHG favourability of the miscanthus-derived product was observed. In the context of agri−/horticultural applications, for example, the use of miscanthus-derived biochar as a soil amendment (Ruett et al. 2024), use phase and EOL may coincide. For this reason, the corresponding aspects have already been discussed in the Section on the use phase.

4.1.5 | Attributional vs. Consequential Approaches and Indirect Land Use Change Impacts

The majority of studies included in this review applied an attributional approach. Product-focused LCAs typically use an attributional approach as suggested, for instance, in the ILCD handbook (ILCD 2010), but there are controversies around the application of attributional and consequential LCA approaches (see e.g., (Brander et al. 2019; Weidema et al. 2018, 2019)). As described above, only three studies took a consequential approach. None of the observations in these studies found a clearly negative GHG mitigation potential of the miscanthus-derived products. The publications selected for this review consider a diverse set of products, which hinders comparisons between them. The fact that two alternative LCA modelling approaches arrive at rather similar conclusions regarding the GHG favourability of miscanthus-based products can nevertheless be considered an indication that strengthens the claimed robustness.

Consequential LCAs aim to incorporate indirect effects such as indirect land use change (iLUC), a form of leakage effect. These indirect effects have the potential to outweigh the environmental benefits of miscanthus-derived applications such as soil carbon sequestration (e.g., Lask et al. 2020). In the examined set of publications, only a single study accounted for the potential indirect impacts related to miscanthus cultivation on land previously used for cereal production and pastoral activities (Schmidt et al. 2015). The potential magnitude of the leakage effect was assessed by accounting for additional production of cereals in North America and soy in South America to counterbalance the increased miscanthus cultivation. Unfortunately, results of the sensitivity analysis were only presented for the production of heat and power, and not for the assessed material application propanediol. Nonetheless, the authors concluded that the production of miscanthus on land formerly used for cereal production or pasture can significantly deteriorate the GHG performance of miscanthus-derived products. For this reason, they recommend using only idle land for miscanthus cultivation. Although this is only a single observation, it is reasonable to assume that iLUC considerations are likely to increase the GHG emissions of miscanthus-derived material applications and thus reduce their relative mitigation potential. However, the extent to which such leakage is happening remains uncertain on account of its high variability in effect size. Due to the potentially substantial influence on the robustness of the GHG favorability of miscanthus-derived products, iLUC impacts should be more closely assessed in future studies on material applications. Cultivation on marginal land is one measure to reduce iLUC (Wicke et al. 2015). For miscanthus cultivation on marginal land is a promising option by virtue of its adaptability to a range of biophysical conditions and substantial stress resistance (Clifton-Brown et al. 2017; Lewandowski et al. 2016).

4.1.6 | Reference Products

The choice of the reference product can considerably influence the relative GHG mitigation potential of miscanthus-derived products. This can be highlighted by drawing on results from the comparison in Schulte et al. (2021). In this study, the relative GHG mitigation potential of the miscanthus-derived alternative ranged between −8% and 91% for a range of reference products. For two fossil-based reference products—expanded polystyrene and stone wool—mitigation potentials of 91% and 80% were reported. For two alternative bio-based reference products made from hemp and flax fibre, mitigation potentials of 75% and 78% were found. For these comparisons, the analysis strongly supports the GHG favourability of the miscanthus-derived product.

However, when compared to wood-based insulation material, the favourability is at least questionable, making the selection of the reference product a decisive parameter for the GHG favourability of miscanthus-derived products. A similar observation for miscanthus-derived polyethylene, as described in Bos et al. (2012) further substantiates this conclusion. For the comparison with fossil-based and maize-, wheat-, and sugar-beet-derived polyethylene, the authors found substantial emission-saving potential for the miscanthus-derived alternative. However, when compared to sugar cane-derived polyethylene, the miscanthus-based solution was found to result in higher GHG emissions.

In general and applying to all material applications, it is to be emphasised that substitution effects—and for this reason also the relative GHG mitigation potential—of using miscanthus-derived products likely decline over time due to changes in electricity mixes (increase in renewables) which will also result in improved GHG performance of reference products, as has been previously discussed for wood products (Harmon 2019; Brunet-Navarro et al. 2021).

4.1.7 | Limitations

It should be noted that the present assessment and discussion of influential parameters is based on a qualitative framework. A more quantitative assessment would be preferable and could have been possible by reproducing the identified studies and observations in a common framework (including consistent setting of system boundaries, handling of multifunctional activities, setup of cultivation system, etc.). Such a harmonised approach was originally intended by the authors. However, this was not possible due to incomplete reporting of assumptions, approaches, and inventories in the majority of studies. For instance, the amount of miscanthus dry matter required to fulfil the functional unit could not be derived for all studies. This was due to weak inventory reporting in some cases, but also for confidentiality reasons in others. This study therefore highlights a wider concern related to scientific LCA conduct which undermines LCA's use as a decision-support tool. A substantial proportion of scientific (and peer-reviewed) LCAs is not sufficiently reproducible, as has been previously shown (see e.g., (Scrucca et al. 2020; Thonemann et al. 2022; Vafi and Brandt 2014)). To further validate the robustness of miscanthus product GHG favourability, inventory reporting needs to be improved to enable meaningful reproducibility under ceteris paribus conditions. This can be achieved by taking minimum publication requirements seriously (see for instance, (Hertwich et al. 2018)). Another important limitation of this study is that the comparison of environmental impacts was restricted to the Global Warming Potential (GWP) indicator. While GWP is a key metric for climate-related assessments, it does not capture other relevant environmental dimensions such as land use, water consumption, or biodiversity impacts. As highlighted in the discussion on potential trade-offs, focusing solely on GWP may overlook unintended consequences or burden shifts to other impact categories. A more comprehensive assessment incorporating multiple environmental indicators would be necessary to fully understand the sustainability implications of the analysed systems.

4.1.8 | Synthesising

It is concluded that the selection of the reference product is a fundamental factor influencing the GHG favourability of miscanthus-derived products (Table 4). Further influential

TABLE 4 | Overview of parameters influencing the relative GHG mitigation potential of miscanthus-derived products; including tentative influence on mitigation potential (in comparison with mitigation potentials shown in Figure 2).

Parameters of interest		Tentative influence[a]	Significance (qualitative)
Biomass cultivation	Commercial management scheme	+	Low[b]
	Soil carbon changes included	+	Medium[c]
	Considering indirect land use change	−	Non-definable
Conversion	Advanced product design	+	Medium
	Advanced process design	(+)	Medium
	By-product(s) considered	(+)	Medium
Use-phase	Temporary carbon storage	(+)	High[d]; low[e]
EOL	Treatment options	/	Low
	Energy recovery included	+	Low
Reference product	Fossil-based	+	High
	Bio-based	−	High

[a]On relative GHG mitigation potential of miscanthus-derived products in comparison with reduction given in Figure 2, + (−) indicating a beneficial (detrimental) influence of the parameter on the relative GHG mitigation potential of the miscanthus derived product.
[b]Assuming commercial miscanthus cultivation.
[c]Applications with high miscanthus content.
[d]Long-lived products with high miscanthus content.
[e]Other products.

parameters encompass the potential incorporation of soil carbon changes, temporary carbon storage (in particular in products with a high miscanthus content by mass) as well as improved product and process design. Studies included in the present review made somewhat conservative assumptions with regard to these parameters (e.g., broadly excluding soil carbon changes, temporary carbon storage, non-commercialised process setups, etc.). Thus, it is expected that GHG impacts of miscanthus-derived material applications are rather over- than underestimated in these studies, which corroborates the GHG favourability observed in the results section. It is concluded that the examined miscanthus-derived products for material applications are likely to exert lower climate change impacts than incumbent reference products.

The only parameter that appears to potentially question this conclusion is the incorporation of iLUC impacts. Their inclusion in LCAs and carbon footprints is strongly debated and a consensual method does not exist (Ahlgren and Di Lucia 2014; Brandão et al. 2021). Even so, it can be concluded that if iLUC effects are minimized, the conclusion of GHG favorability of miscanthus-derived products can be considered robust for the products assessed in the included studies. Here it is to be emphasized that miscanthus is ideally suited for cultivation on marginal or residual land, as well as on areas designated for biodiversity or other regulated environmental purposes (Clifton-Brown et al. 2023). Prioritizing such areas helps to minimize the risk of iLUC.

4.2 | Implications for Further Development of Miscanthus-Derived Products

4.2.1 | Maximising the Contribution to Climate Change Mitigation

Ideally, a miscanthus-derived product for material applications should achieve a maximum contribution to climate change mitigation. The parameters described above are those that should be kept in mind when incentivising the further development and commercialisation of miscanthus-derived material applications. This means, for instance, that miscanthus-derived products which substitute more GHG-intensive conventional products should be given preference over other alternatives. The biomass for these products should ideally be derived from plantations that result in an increase in soil carbon and have a low risk of inducing iLUC. In addition, long-living products are to be preferred.

A further aspect should, however, also be considered: given the constrained global biomass availability, applications that maximize the absolute GHG emission reduction per unit biomass used should be preferred. The ratio of absolute GHG emission reduction per unit miscanthus biomass required could be used as a basis for information on the favorability of a selection of potential applications. Unfortunately, it was not possible to derive this indicator for all observations included in this study as information on the amount of biomass required per functional unit was not abundantly reported (see section on limitations above). This emphasizes once more the importance of ensuring reproducibility of studies on miscanthus-derived applications by increasing transparency and accessibility of data. Nonetheless, it is to be expected that long-living material applications in particular, for example, in the construction sector, could provide disproportionally high absolute reduction potentials (as also observed in studies in the forestry sector; see for instance (Smyth et al. 2020)).

4.2.2 | Markets

A product is not only produced for its GHG emissions favourability. For this reason, market acceptance must also be considered. A comprehensive analysis of the market potential of miscanthus-derived material applications was, however, beyond the scope of this study. Regulatory issues continue to prevent the market entry of innovative biobased materials (Pender et al. 2024). This applies, for instance, to miscanthus-derived insulation materials in the construction sector, which cannot be approved by certification bodies due to the absence of testing and supervision formalities. Such market entry barriers have to be tackled by legislation. In addition, the higher prices of innovative biobased products in comparison with conventional reference products remain a substantial barrier to a wider market entry of biobased material applications (Sand Jespersen et al. 2019). However, price competitiveness is likely to improve with an increasing relevance of CO_2 prices as these will result in higher costs of fossil-based alternatives (van den Bergh and Savin 2021). Miscanthus-derived products that tend to have lower GHG emissions than conventional (in particular, fossil-based) reference products will disproportionally benefit from such schemes. In addition, the implementation of CO_2 certification schemes—such as those already established in the biochar sector (Thengane et al. 2021)—can offer additional revenue streams for producers of bio-based alternatives by monetizing potential carbon sequestration. Complementing these aspects, consumer acceptance will be decisive for the market entry of miscanthus-derived products.

In addition, the feasibility of ensuring a sustainable supply of both the required biomass and the final product should be taken into account. Keeping the limited global availability of agricultural land in mind, the choice of target markets and their potential size should be considered when making decisions on product selection: Applications oriented towards larger market volumes, requiring substantial quantities of miscanthus biomass, are more likely to result in competition with other land uses and thus indirect effects. Ideally, these niche market applications could be supplied with feedstock from low-iLUC risk land such as buffer stripes (Agostini et al. 2021; Ferrarini et al. 2017).

4.2.3 | Managing Trade-Offs With Other Environmental Impacts

Even if a miscanthus-derived product for material application promises a higher GHG mitigation potential compared with other alternatives, environmental impacts beyond GWP should also be considered. This is as trade-offs are commonly identified in LCAs of biobased miscanthus-derived products if environmental impact categories beyond climate change are assessed (Lask, Kam, et al. 2021; Schmidt et al. 2015). Fourteen out of twenty studies included in this review assessed a broad set of environmental indicators drawing on established impact assessment methods such as the ReCiPe family (Goedkoop et al. 2008; Huijbregts et al. 2017) and TRACI (Bare 2011). Five studies—3, 14, 15, 17, 19—focused on climate change impacts alone, at least in terms of environmental indicators. The absence of trade-offs was reported for three observations in Schulte et al. (2021) (1.1.4 and 1.1.5), where miscanthus-derived insulation material was compared to hemp fibre- and flax-based alternatives and Roy, Defersha, et al. (2020), where miscanthus-reinforced polypropylene (PP) is compared to talc-reinforced PP (9.1.1).

For all other observations at least, some trade-offs were reported. Most typically, a less favorable performance of miscanthus-derived applications was reported in terms of acidification, eutrophication, ecotoxicity, human toxicity, ozone formation, and land use impacts. These are impact categories where biobased products usually perform worse than fossil alternatives (Zuiderveen et al. 2023). As such, miscanthus-derived products are likely to perform less favorably, especially when compared to fossil- or mineral-based reference products. Here it should be emphasized that eutrophication impacts in the studies assessed are likely to be overestimated as generic models are widely used for modeling nitrate and phosphate leaching. However, these generic models do not sufficiently represent perennial cultivation systems such as miscanthus, which are effective in reducing nitrate leaching (Curley et al. 2009; Studt et al. 2021) and, particularly in commercial practice, require only low levels of nitrogen application compared to annual cultivation systems. Environmental impact categories beyond climate change should thus be intensively monitored in future sustainability assessments of miscanthus-derived products.

Miscanthus-derived products for material applications have the potential to contribute to GHG mitigation if the risk of iLUC effects can be reduced. Given the limited availability of agricultural land, miscanthus-derived products with high absolute GHG mitigation potentials per unit of used biomass should be preferred. Potential environmental trade-offs are likely to occur and need to be considered and managed. To provide stakeholders with more comprehensive information, the reproducibility of future LCAs on miscanthus-derived material applications needs to be improved by increasing data transparency and accessibility. More transparent reporting of assumptions and inventory information will enable the use of publications in review and meta studies such as the present one and support the drawing of more quantitative conclusions on the use of miscanthus-derived products.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are openly available in Zenodo at https://zenodo.org/records/17615171.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Data S1:** gcbb70099-sup-0001-Supinfo.xlsx.