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Review

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Carbon footprints of European dairy farming: the role of drained peatlands in GHG assessments

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Climate change is driven by rising greenhouse gases, with food systems contributing a third of emissions. Dairy farming plays a key role, yet LCAs often omit emissions from drained peatlands, which are estimated to release an average of 31.7t CO_2-eq/ha/year used as grasslands. This review highlights the need to integrate soil organic carbon losses into LCAs, as their omission distorts carbon footprints and hinders effective mitigation strategies for reducing dairy-related greenhouse gas emissions.

Despite covering only 3% of the global land surface, peat soils are significant carbon reservoirs, accounting for one third of the world's soil carbon which is approximately twice as much carbon as the biomass of all forests worldwide[1–3]. This makes peatlands not only valuable ecosystems but also gives them a highly influential role when it comes to global greenhouse gas (GHG) emissions and climate change mitigation[1,2,4,5]. However, together with increasing land use (LU) intensification, the majority of peatlands have undergone extensive drainage for agricultural purposes in recent decades and centuries, turning them from highly important carbon sinks to one of the largest human-induced sources of GHG emissions worldwide[6–8] (Fig. 1). The ongoing degradation of these valuable peat soils leads to substantial release of carbon dioxide (CO_2) through peat oxidation, thereby exacerbating GHG emissions[9–11].

This issue is particularly relevant for the dairy sector, as many drained peatlands are used as grasslands for feed production, directly linking them to milk production[12]. Dairy production plays a key role in European agricultural economy, representing one of its most important and profitable sectors[13,14]. However, this vital industry contributes to one third of GHG emissions of the global livestock sector and 4% of the total anthropogenic GHG emissions worldwide[15,16]. Faced with urgent climate targets, such as the overarching goal to reach climate neutrality by 2050 under the European Green Deal, there is increasing pressure on the agricultural sector to implement efficient climate mitigation strategies[14,17,18].

Life Cycle Assessment (LCA) is an established tool that uses input-output calculations during a product's life cycle, finally resulting in a Carbon footprint (CF)[19–22]. This systematic approach helps to identify major GHG emission sources, making it a powerful tool regarding the development of efficient mitigation strategies[20,23,24]. While LCA represents a widely adopted and established methodology, a critical gap still persists: the substantial GHG emissions originating from drainage and management of peatlands for agricultural use are largely overlooked in current CF calculations in milk production[17,25–28].

Given the potentially great contribution of these emissions, their omission leads to a fundamental underestimation of the true CFs of dairy products, such as milk, originating from agricultural peatlands.

This paper aims to provide a comprehensive overview of the theoretical background of drained peatlands, their ecosystem functions as well as the role of dairy farming in Europe and the fundamental principles of LCA relevant to agricultural emissions. Building up on this foundational knowledge, the second objective is to provide a systematic review of existing LCA studies with a specific focus on European milk production. Based on this approach the paper aims to (1) identify the extent to which GHG emissions from drained peatlands are considered in LCAs of European agricultural products, with a specific focus on milk production (2) assess the methodologies applied in relevant studies for including peatland emissions and (3) to explore potential mitigation strategies to reduce these emissions.

Theoretical background: Peatlands, agricultural GHG emissions and LCA fundamentals

This chapter provides the essential theoretical background necessary for understanding the critical role of peatlands in agricultural GHG emissions, their natural ecosystem functions as well as the application of LCA in the dairy sector.

Peatland ecosystem functions

Peatlands represent unique and complex ecosystems that play a key role in providing multi-faceted ecosystem services[29,30] (Fig. 2). Hereby, the list of beneficial functions is long, ranging from being a source of fiber, fuel and food, contributing to climate and air quality regulation, water storage and purification as well as to erosion protection, to providing recreational areas

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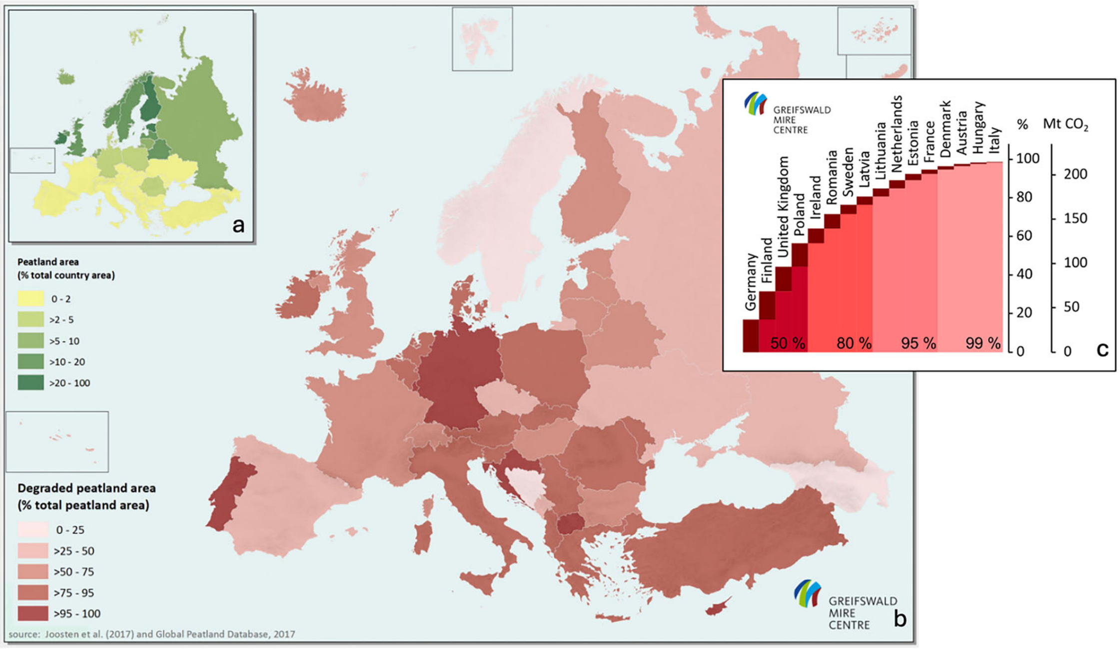


Fig. 1 | Map of peatland area in Europe and their state of degradation. a The map shows the percentual distribution of peatland area within European countries as well as their state of degradation (2017). **b** As a very large proportion of peatland area is found in Nordic countries, the Baltic area and the UK (c) the state of degradation and, thus contribution of CO_2 emissions, is the highest in Germany (2019). Adapted with permission from Greifswald Moor Centre – Global Peatland Database (GPD, 2015 & 2019).

Fig. 2 | Peatland ecosystem services. Peatlands represent unique and complex ecosystems providing multiple ecosystem functions on the levels of provisioning, regulating, cultural and supporting ecosystem services ranging from offering fiber, fuel and food source, contributing to climate and air quality regulation, water storage and purification as well as to erosion protection, to providing recreational areas and places that are characterized by high biodiversity, soil formation and nutrient cycling, including the nutrient's storage, recycling, processing and acquisition. Created using Microsoft PowerPoint.

and places that are characterized by high biodiversity, soil formation and nutrient cycling[30,31]. In intact peatland ecosystems, the formation of organic soils results from the prevailing oxygen deficiency caused by high-water tables[8,11]. In contrast to mineral soils, these are characterized by their high density in carbon (C) and nitrogen (N), with organic matter contents often exceeding 90%, and a depth up to several meters[11,32,33]. They store approximately 21% of the total global soil organic C stock, estimated to approximately 3000 Gt of C, underlining their importance in C storage and sequestration[11,34,35]. This ability makes peatlands a large C sink and thus a key player in climate regulation and cooling. On the other hand, anthropogenic intervention, such as land use change (LUC) accompanied by the drainage of peatlands or fires, that result in a decrease of moisture, stored C can also be released into the atmosphere, transforming peatlands from C sinks to C sources[11,36–39]. But also rising temperatures and droughts associated with global warming impose additional pressures on peatland ecosystems, further compromising their integrity and functionality[29].

Agricultural land use and GHG emissions from European peatlands with a focus on milk production

Globally, about 65 million hectares, i.e., 16% of the peatland area in the world have been drained[40,41]. In Europe, this figure is significantly higher, with nearly half (approximately 46%) of the total peatland area having undergone drainage[40,42]. While European peatlands are predominantly found in Nordic countries within the boreal zone, significant areas also exist in the temperate zone including Ireland, the UK and Baltic countries. From Central towards Southern Europe, peatland cover becomes rather sparse and is mostly found in river valleys and pre-alpine areas (Fig. 1)[43,44].

One of the main reasons behind the extensive drainage of peatlands over centuries, has been their conversion into agricultural soils. Dairy production, a highly profitable sector of the EU, is a major contributor to this LUC[13,14]. Drained peatlands, in particular, are frequently converted to grasslands for dairy feed[15,16]. At farm-level the primary sources of GHG emissions stem from animal husbandry, primarily from enteric fermentation and manure management, and the management of agricultural soils, such as manure and fertilizer application, with the three GHGs methane (CH_4), CO_2 and nitrous oxide (N_2O) being the main contributors[45–47].

Drainage of peat soil removes water and aerates the peat layer resulting in aerobic decomposition with associated GHG emissions (Fig. 3). Global CO_2 emissions resulting from oxidative decomposition of drained peatlands have been estimated to total 1.15×10^9 t CO_2[35,40]. Beyond GHG emissions, drainage is associated with nutrient loss, loss of biodiversity, reduced water retention capacity among many other factors. Finally, the physical collapse of peat soil leads to its shrinkage, resulting in loosening thickness up to several centimeters per year[6,30,40]. Thus, drainage ditches have to be deepened on a regular basis in order to maintain low water tables, which can eventually result in the destruction of productive land[35,40]. Against this background, agricultural peatlands also face substantial challenges to farmers associated with their long-term utilization. Specifically for milk production on these drained peatlands, GHG emissions expressed in CO_2-equivalents (CO_2-eq) are estimated to have a multiple times higher CF than on mineral soil (Fig. 3)[3,48–52]. This highlights the key role of peatlands in the agricultural context[3,48], particularly within the dairy sector and contributes to rising pressure on the agricultural sector to reduce their environmental footprint. This pressure is further driven by ambitious targets as the European Green Deal aiming for climate neutrality by 2050, which necessitates effective mitigation strategies targeting major contributors to global warming, including dairy farming[14,18,45].

Fundamentals of LCA in milk production

LCA represents a method frequently used to estimate CFs by considering production in terms of relative impact per unit of product, such as one kilogram or liter of milk[15,53]. The CF is assessed according to International Organization for Standardization (ISO) guidelines, providing a standardized method[54]. While LCAs can assess various impact categories, the global warming potential (GWP) is the most frequently considered category and directly reflects the CF. One key distinction in LCA methodology is between attributional LCAs (aLCAs), assessing the average CF of a product under current conditions, and consequential LCAs (cLCAs), estimating the system-wide impact of changes in production or demand. While aLCAs provide a snapshot of emissions based on existing supply chains, cLCAs account for indirect effects, commonly leading to different results (Fig. 4)[55–57]. These methodological choices along with system boundaries, allocation methods, data availability are significant sources of uncertainty in LCA results[55,58–62].

Methodological challenges and uncertainties. Despite standardized guidelines and the widespread use of LCAs, several methodological challenges can complicate comparability and accuracy of CF assessments[55,58–62]. Additional uncertainties can arise from the use of standardized values for emission-related parameters such as feed composition and transport emissions, which can vary across farms and geographical locations[28,47]. For example, assumptions such as increasing the milk yield to lower CFs of milk can be strongly dependent on the enteric CH_4 conversion factor (Ym-%) that has been used in the respective LCA, ranging from simplistic approaches (IPCC 2006) to complex functions differentiating between the feed fiber content and the Ym-values, to fully capture their relationship (GLEAM-bases estimations)[63–68]. But also tracing the origin of purchased feed ingredients, can represent a major challenge[28,69,70]. Moreover, the diversity of dairy farming systems across Europe, including differences not only in management practices, but also climate and soil properties, makes

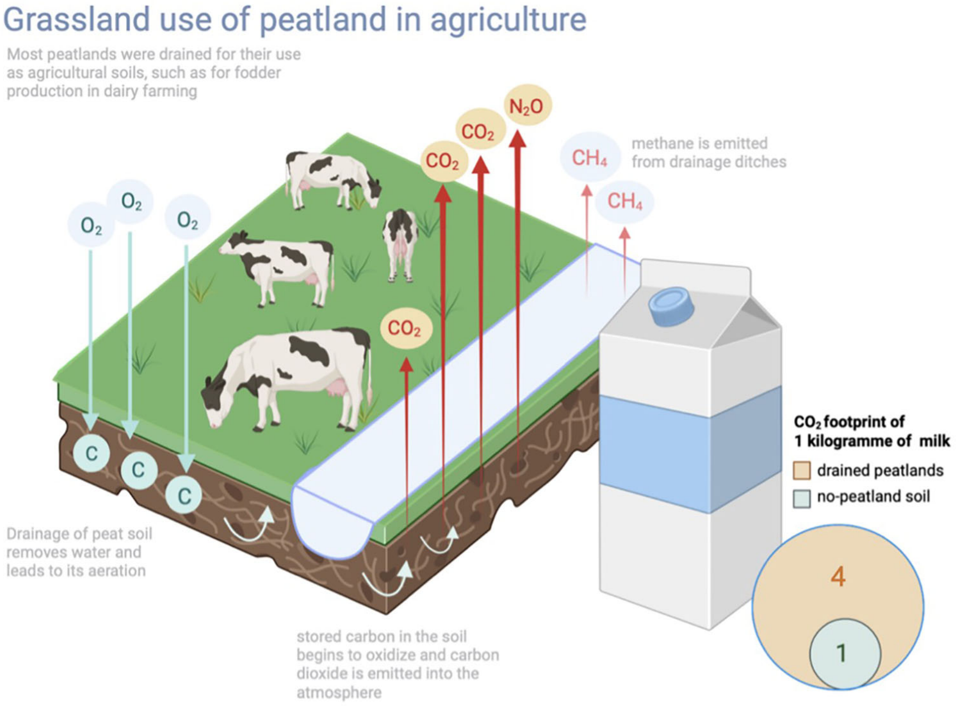
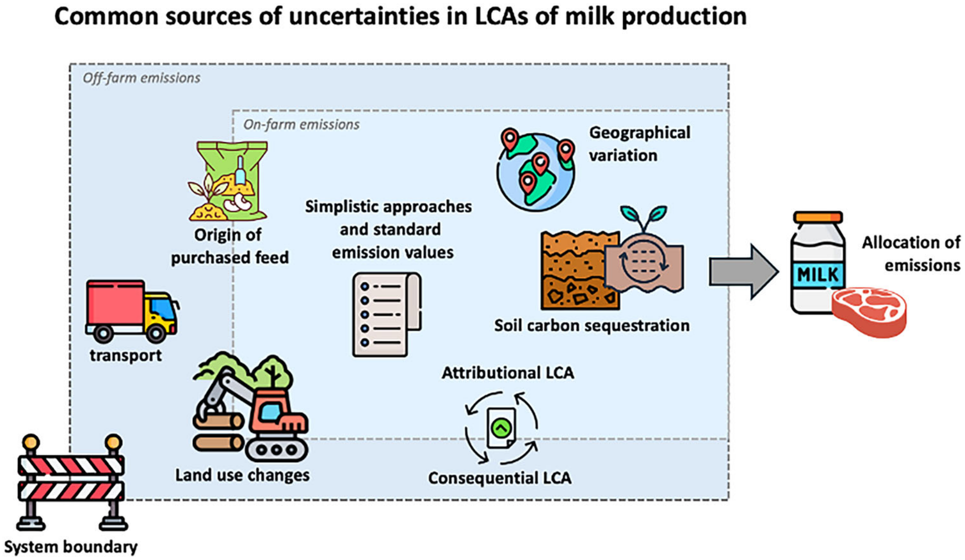


Fig. 3 | Emission sources in drained peatlands of agriculture and dairy farming and their potential impact on milks CF. Drainage of peat soil removes water, thus leads to its aeration, so that aerobic decomposition takes place that is accompanied by the emission of GHGs. Along with the drainage, nutrient loss with the received water is observed together with a loss of biodiversity and reduced water retention capacity among many other factors. Finally, the physical collapse of peat soil leads to its shrinkage, resulting in losses of its thickness up to several centimeters per year, whereas methane is emitted from drainage ditches. Finally, the production of milk on drained peat soil is estimated to result in multiple times higher CF compared to milk production on no-peat soil[3,49]. Created using Microsoft PowerPoint.

Fig. 4 | Common sources of uncertainties in LCAs of milk. The illustration shows different fields and methodological choices of potential uncertainties arising during the conduction of LCAs for calculating CFs of milk, that are commonly discussed. Created using Microsoft PowerPoint.



generalization and the use of standard emission factors (EFs) difficult, frequently leading to a lack of region-specific data and appropriate representation[53,71,72]. Also, treatment of direct and indirect LUC emissions, particularly from deforestation related to feedstock production, represents another source of uncertainty: While there is increasing recognition of the impact of LUC on GHG emissions, different methodologies for LUC calculations lead to vastly different results[56,70,73]. However, studies have shown that including LUC can increase the CF of milk by up to 877%[70], highlighting both the necessity of its inclusion and the need for a standardized methodology. Additionally, study objectives vary widely, affecting comparability. While some studies focus on more ‘general’ CF assessments[15,17,59,73], others examine specific measures such as breed differences, replacement rates or manure management[74–76]. The handling of co-products, such as meat and manure, further complicates CF comparisons, as different allocation methods significantly influence results[55,61,72,77]. Similarly, soil carbon sequestration is rarely incorporated in LCAs, despite grasslands playing a crucial role in C storage[28,78,79]. Soil characteristics significantly influence CFs, acting as sinks or sources depending on their management[76,79,80]. Some studies indicate that accounting for soil carbon sequestration can significantly lower the CF of milk, particularly in grass-based dairy systems[76,81–83]. However, methodological challenges and limited data on soil carbon dynamics hinder consistent integration[82,84,85].

Beyond these frequently discussed issues, another potential source of uncertainty arising from the omission of emissions from drained peatlands, is often overlooked. Unlike grasslands on mineral soils that can act as important C sinks, many are the result of drained peatlands, releasing massive amounts of soil carbon instead[86–88]. Agricultural use of drained peatlands emits significantly more GHGs than mineral soils, yet these emissions are often excluded in CF calculations.

General LCA findings and common mitigation strategies. Most LCAs on milk production in Europe follow a “cradle-to-gate” perspective, covering both off-farm and on-farm processes. Commonly included factors are the production of feed and concentrates, fertilizers, fuel, and electricity (off-farm) as well as on-farm processes, including internal feed production, fertilizer use and manure management, animal husbandry and energy consumption[28]. Hereby, feed efficiency and milk yield per cow have been frequently observed as one of the most influential factors in terms of its GWP (Fig. 5)[17,28]. Studies showed that high reliance on purchased concentrates leads to greater emissions due to energy use and transport, while roughage-based diets increase enteric methane (CH_4) emissions and can lead to higher land requirements[28,89]. Optimizing the feed composition and on-farm feed production can reduce emissions, particularly by minimizing external feed imports, which are often linked to LUC, such as deforestation for soybean cultivation (Fig.)[73]. Additionally, transitioning from conventional to organic farming can lower emissions from synthetic fertilizers and soil management, although reduced milk yields in organic systems can counterbalance the benefits of this mitigation strategy[15,55]. Other potential strategies include optimizing manure management and improving animal health and longevity[75,90].

Conventional LCAs, despite their broad scope and methodological discussions, frequently overlook GHG emissions from drained peatlands, as critical component for effective GHG mitigation. This omission represents a fundamental gap, leading to an incomplete picture of the environmental footprint of milk production, particularly in regions where dairy farming is prevalent on organic soils. It is precisely this omission that the following systematic literature review aims to investigate by examining how, and to what extent, these crucial emissions are addressed in existing LCA studies of European milk production.

Methods

This study employed a systematic literature review to identify and analyze peer-reviewed research on LCA of dairy production, specifically focusing on the inclusion of emissions from drained peatlands in Europe. The review followed a structured approach, beginning with a systematic literature search conducted in Scopus (www.scopus.com) (Fig. 6).

The initial search query combined key terms related to dairy production (“milk production,” “dairy farming”, “milk,” “dairy”), environmental impact assessments (“LCA”, “life cycle assessment”, “CF”, “greenhouse gas emissions”), and organic soils and peatland conditions (“drained peatlands”, “organic soils”). To ensure geographical relevance, the search was restricted to studies within Europe or any of its countries (Fig. 6).

Additional filters were applied to include only peer-reviewed journal articles published in English between 2015 and 2025. The search was further limited to final publication stages and included only open-access articles. This approach aimed for a comprehensive yet targeted selection of recent literature. This initial search yielded in 162 articles. To further focus on articles considering drained peatlands in milk production and dairy farming, these results were filtered using the keywords “organic soils” “peat soil” and “dairy farming”, which narrowed the results down to 12 articles (Fig. 6). To ensure the studies focused on LCA methodology, the search was further refined by adding “life cycle assessment” as a mandatory search term within

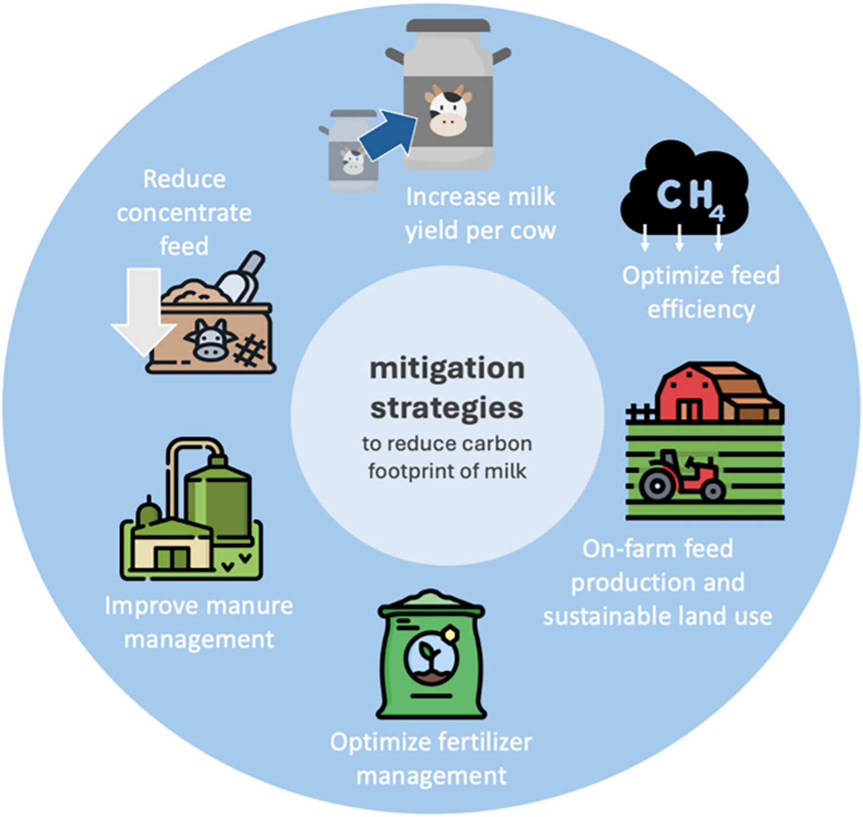


Fig. 5 | Common mitigation strategies to lower the CF of milk production. The increase of milk yield, optimizing diets and feed efficiency, improve manure and land management are commonly discussed as levers in mitigating the CF of milk production based on LCA approaches. Created using Microsoft PowerPoint.

the remaining 12 articles, resulting in 9 studies. The abstracts, and where necessary, full texts of these 9 articles were then thoroughly screened against pre-defined inclusion and exclusion criteria. Inclusion criteria comprised peer-reviewed articles published in English within the specified timeframe, focused on LCAs of milk/dairy production in Europe, and explicitly addressing GHG emissions from drained peatlands. Exclusion criteria included studies located outside Europe ($n = 1$) and studies that did not directly address the specific methodological aspects of LCA or the explicit role of drained peatlands in dairy GHG emissions ($n = 3$).

This screening process resulted in a final set of 5 articles for detailed review (Tab. 1). The entire search and screening process is summarized in Fig. 6. For each of the selected articles, relevant data were systematically extracted, including study objectives, geographical scope, use of LCA methodology and specific approaches or mentions of GHG emissions from drained peatlands. The extracted data were then qualitatively synthesized to identify common themes, recurring methodological approaches, prevailing uncertainties, and key findings regarding the inclusion of drained peatland emissions in dairy LCAs. The analysis also aimed to identify specific challenges in incorporating these emissions and to highlight proposed solutions or future research needs.

Results

The literature review reveals a significant gap in specific LCA studies addressing the role of drained peatlands in milk production. Only two of the studies identified for the literature review apply typical aLCAs in the context of drained peatlands[52,91], and only van Boxmeer et al.[52] used energy-corrected milk (FPCM) as functional unit (FU), allowing for direct comparison of milk output (Table 1)[52,91]. Despite this lack, substantial body of literature and growing interest in the general role of peatlands can be observed, particularly concerning their rewetting and use as paludiculture for climate change mitigation.

This is consistently shown by the present literature review, where a range of studies examined the environmental and economic impacts of LU options on drained peatlands, focusing on GHG emissions, climate change mitigation potential, and the viability of alternative LUs.

Liu et al.[92] compared the ecosystem services of six LU options on former conventionally farmed peatlands, including dairy farming, using an environmental system analysis (ESA) approach similar to a partial cradle-to-farm-gate LCA[92]. Their findings indicated that conventional drained dairy farming yielded in low ecosystem services but high environmental costs, while organic farming, though improving regulation services, remained insufficient. Paludiculture, conversely, enhanced sustainability but demanded high investment and policy support. Significantly, Liu et al.[92] calculated emissions from drained peatlands using a formula directly relating water table depth to CO_2 emissions from organic soils, confirming that drainage-based systems emitted the highest CO_2 amounts[92].

Similarly, de Jong et al.[91] assessed and compared the GWP of dairy production as a reference system and cattail cultivation on Dutch peatlands as an alternative system[91]. This study explicitly used LCA, adopting a cradle-to-gate perspective with 1 ha of Dutch peatland as the functional unit to reflect LUC[91].

Their results demonstrated that cattail paludiculture significantly reduces emissions from drained peatlands, primarily due to higher groundwater levels, though economic viability remains a key challenge for system change. CO_2 emissions from drained peatlands in the reference dairy system were calculated using a formula based on the mean annual water table, indicating emissions up to 30t CO_2-eq/ha when the water table is below 40 cm. Direct comparison within this study showed that transitioning from drainage-based dairy farming to cattail paludiculture could lead to a reduction of approximately 16.4 tons of CO_2-equivalent per hectare of Dutch peatland annually [93], primarily due to decreased emissions from peat oxidation resulting from changes in LU management.

Analysis of farm-level data on dairy farms located on both peat and sandy soils, using a LCA approach, was conducted by van Boxmeer et al.[52], to evaluate their GWP and economic performance, using FPCM as a functional unit[52]. Data of Dutch dairy farms on both peat and sandy soils was

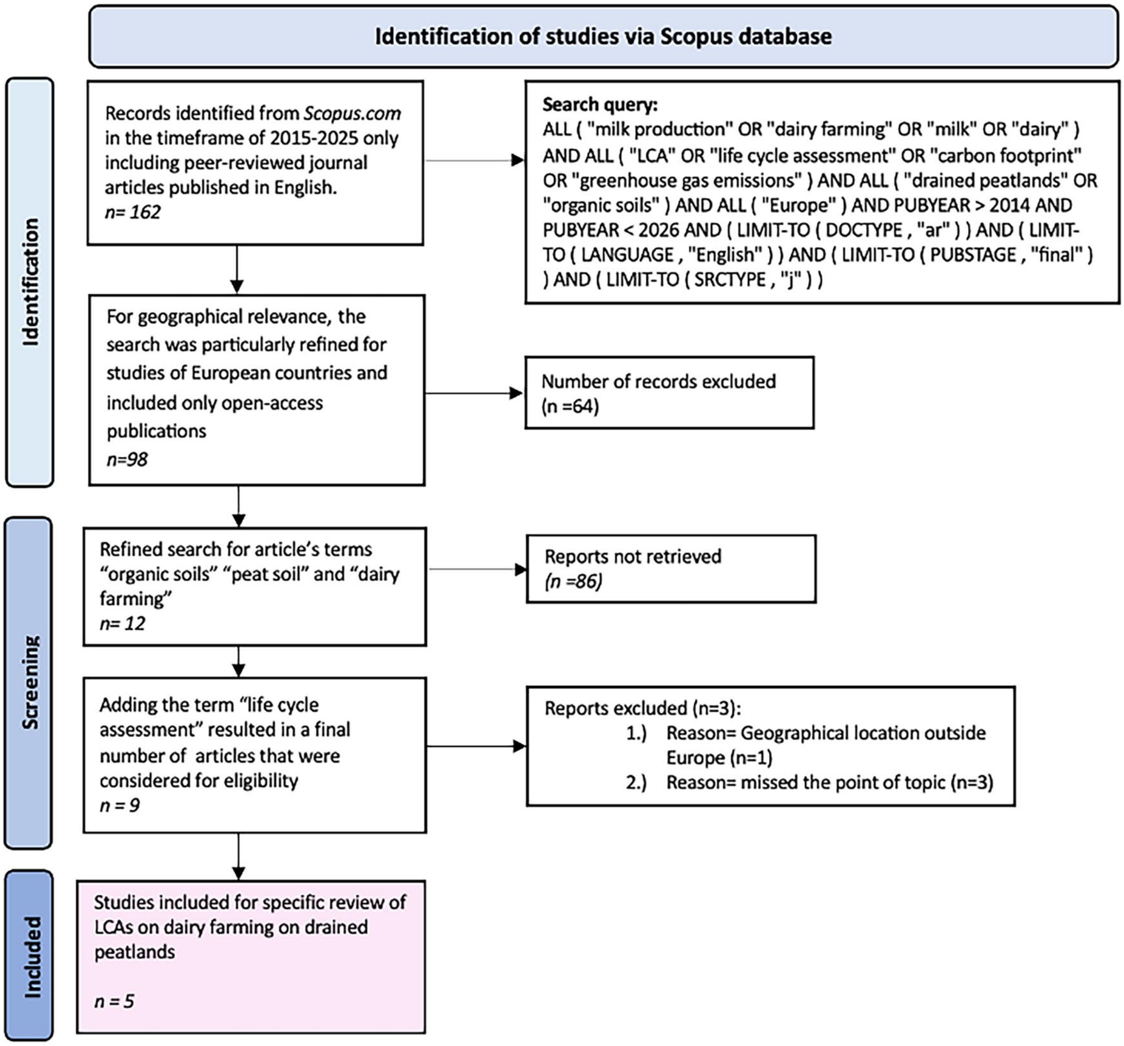


Fig. 6 | Flowchart of literature review. The scheme shows the identification and screening strategy and process of studies regarding LCAs of dairy farming in the context of drained organic soils or peatlands within European countries, that were reviewed in more detail. Created using Microsoft Word.

used, focusing on differences in management practices, water table depths, and intensification. The analysis demonstrated considerably higher emissions of dairy farms on peat soils, due to 1,32 kg CO_2-eq per kg FPCM attributed to emissions from peat oxidation[52]. This study underscored the significant impact of peat soil drainage on increasing GHG emissions in dairy farming through the use of empirical emission factors related to water table depth[52]. It was also shown that from an economic perspective, while paludiculture offers a sustainable alternative, its viability depends on improving market conditions and policy frameworks to make it economically competitive with conventional dairy farming[52,93,94].

Although, economic performance under current market conditions might remain stable, profitability declines with stricter environmental regulations[93]. Thus, economic performance of peatland agriculture depends heavily on subsidies for peatland conservation, particularly through practices that maintain higher water tables (Fig. 7)[52].

Furthermore, Roesch et al.[93] focused on developing environmental indicators for farm-level assessment within Swiss agri-environmental policy goals. While not a full LCA, their approach also modeled CO_2 emissions from drained peatlands based on water table depth, emphasizing the need for accurate water table data and suggesting the use of standard EFs for drained organic soils when specific data is unavailable[93]. They found that existing direct payment systems for environmentally friendly agriculture were unsuitable and proposed a novel, flexible, and transparent indicator-based system. Lastly, Rebhann et al.[94] evaluated the economic viability and labor requirements of different LU practices on German fenlands using a hypothetical farm model[94]. They observed that intensive management systems on fenlands lead to increased GHG emissions, especially on drained peat soils. However, specific CO_2 emission values from drained peatlands were not calculated within their analysis, nor did they conduct a full LCA[94]. Nevertheless, their study highlighted that most management systems on fenlands are profitable only with subsidies and ecosystem service payments, supporting peat-saving agricultural practices[94].

The detailed review of these five studies reveals a critical distinction. While all studies acknowledge the environmental impact of drained peatlands in the agricultural context, only two studies employed LCAs to evaluate the entire environmental impact of different LU systems and directly compare their CFs, and only one consistently used FPCM as a functional unit[52]. Most of the studies compared dairy farming with paludiculture or rewetting, which highlights the emission dynamics and impact of peat soils but does not provide a complete CF of milk production.

The literature consistently showed that drained peatlands have a strong environmental impact due to high CO_2 emissions, with calculations of CO_2 emissions from peatlands mostly relying on water table depth as a key variable. Transitioning from traditional farming systems to sustainable alternatives like paludiculture or rewetting was shown to significantly reduce CO_2 emissions whilst even in some studies increasing carbon sequestration[52,91,92]. However, their widespread economic feasibility still

Table 1 | Overview of identified studies within the literature review

Study objective	Experimental setting	methodology	Main results	Relevance to Peatlands	Use of LCA	Ref.
Comparison of ecosystem services of six land use options on former conventionally farmed peatlands to identify sustainable alternatives to drained agriculture.	Conceptual model farm systems for each land use including conventional and organic drainage-based dairy farming, low-intensity grasslands for grazing at medium water levels, and high-intensity paludiculture at high water levels.	Environmental system analysis (ESA) approach on modeled farm systems defined by literature-based inventory analysis, similar to the cradle-to-farm-gate partial LCA. Five ecosystem services as indicators of environmental impacts with a FU of 1 ha peat soil.	Conventional drained dairy farming shows low ecosystem services, but high environmental costs, organic farming improves regulation services but remains insufficient, while paludiculture enhances sustainability but demands high investment and policy support.	Emissions from (drained) peatland were calculated using a formula highlighting the relationship between water table depth and CO_2 emissions from organic soils. Drainage-based systems showed to emit highest CO_2 amounts.	✗	92
Assess and compare the environmental impact of dairy production (reference system) and *Typha* (cattail) cultivation on Dutch peatlands (alternative system)	Model of Reference system (RS) for dairy production and alternative system (AS) for paludiculture. RF was based on case study data in the Netherlands with peat soil properties, subsidence rates, GHG emissions, average milk production of 2018. The AS model was literature-based.	LCA was used to assess the environmental impact of both systems using the GWP as indicator, a cradle-to-gate perspective and 1 ha of Dutch peatland as FU to reflect LUC.	Dutch *Typha* paludiculture showed a significant climate change mitigation potential by reducing emissions from deep drained peatlands mainly due to peat decomposition at a higher groundwater level. But increasing economic viability is needed for system change.	CO_2 emissions from drained peatlands were calculated in the RS with a formula based on the mean annual water table, suggesting a water table <40 cm, leads to emissions up to 30t CO_2eq/ha	✓	91
Development of environmental indicators to assess farm-level environmental impact within Swiss agri-environmental policy goals	Three indicator-based systems with varying complexity (simple, medium, and detailed) for farm-level assessment of environmental impacts in Switzerland were developed and tested.	Key environmental areas such as GHG emissions, nutrient leaching, biodiversity, and soil health were assessed using the three indicator systems developed through literature review and expert consultation. Also, feasibility, accuracy, and practicality of each system was assessed in a comparative analysis.	A novel indicator-based direct payment system for environmentally friendly agriculture was developed, as existing systems were found unsuitable. The new system offers flexibility and transparency, but further farm-level testing is needed to evaluate its practicality and farmers influence on payments.	The study modeled CO_2 emissions from drained peatlands based on water table depth and highlights the need for accurate water table data to predict emissions. It is also suggested to use standard EFs for drained organic soils when data is not available.	✗	93
Evaluation of the GWP and economic performance of Dutch dairy farms on peat compared to sandy soil and their financial viability	Data from Dutch dairy farms located on peat and sandy soil was collected with a focus on differences in management practices, water table depths, and intensification levels. The farms showing different drainage depths were compared to determine the impact of water management on emissions and profitability.	Farm-level data collection, environmental impact assessment and economic analysis. GHG emissions, nitrogen surpluses, and other environmental indicators, but also financial performance assessed. The research integrates LCA principles and empirical farm data, whereas fat and protein corrected milk (FPCM) was used as FU.	Drained peatlands significantly contribute to high CO_2 emissions. While intensively managed farms achieve higher milk yields, they also exhibit greater environmental burdens. Economic performance remains stable under current market conditions, but profitability declines with stricter environmental regulations on peatland.	CO_2 emissions from drained peatlands were calculated using empirical EFs that relate greenhouse gas emissions to water table depth. The significant impact of peat soil drainage on increasing GHG emissions in dairy farming is emphasized.	✓	52
Evaluation of the economic viability, labor requirements of different land use practices on German fenlands	Modeled hypothetical farm on German fenland with data inputs including crop yields, livestock outputs, product prices, subsidy rates, and operational costs. Environmental payments, especially for maintaining higher groundwater levels to conserve peat, were considered.	20 management practices in four land use systems were analyzed. Costs, income, and net return was calculated for each system. According to the outcome of the analysis, management systems were categorized in profitable, low profitable, and unprofitable on the farm scale.	Most management systems on fenlands are only profitable with subsidies and ecosystem service payments to support peat-saving agricultural practices. Intensive management increases labor demands per hectare, potentially benefiting rural employment.	It was found that intensive management systems on fenlands lead to increased GHG emissions, especially on drained peat soils. However, specific CO_2 emission values of drained peatlands were not calculated.	✗	94

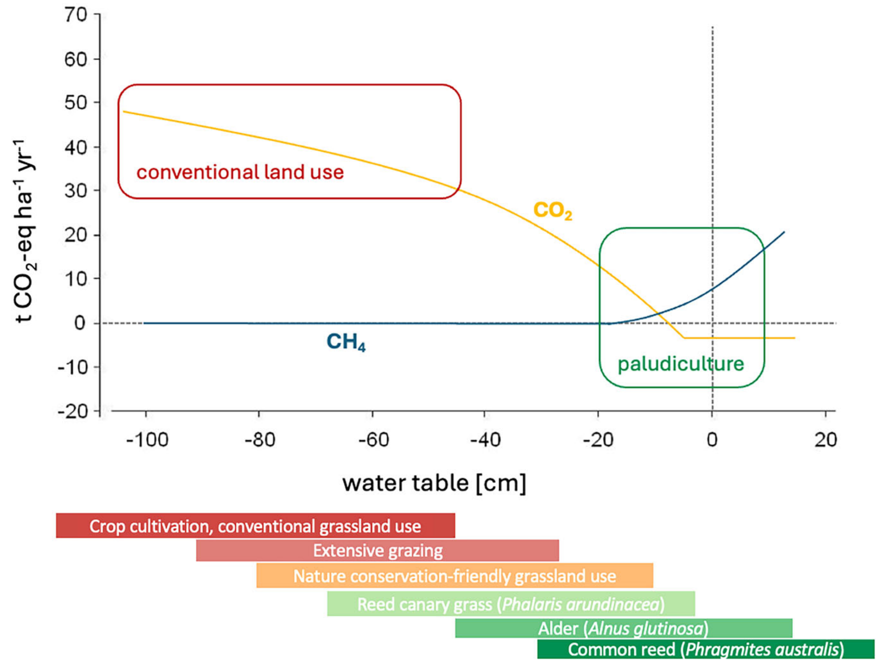


Fig. 7 | Estimated GHG emissions and land use options depending on water table depth -a representation under optimal conditions. Raising the water level can result in a significant reduction of GHG emissions (neglecting N_2O), especially regarding CO_2 [116,128]. Paludiculture may even have the potential of CO_2 sequestration, but cultivation of new agricultural crops is required, such as prodcutive reed canary grass, alder or common reed[129]. Moreover, region-specific conditions have to be considered for the true potential of GHG emissions reductions by rewetting of organic soils[128]. Adapted to own visualization from Succow M. and Jeschke L. in "Deutschlands Moore: Ihr Schicksal in unserer Kulturlandschaft"[130].

depends heavily on environmental payments, improved market solutions, and robust policy support[52,93,94].

Discussion

Although only few studies have been identified in the context of LCAs of milk production on drained peatlands, or perhaps exactly for that reason, the gap of including peat soil emissions within agricultural LCAs becomes obvious.

Failing to distinguish between carbon sequestration in mineral soils, although soil organic carbon is widely assumed to be under equilibrium in CF calculations, and emissions arising from drained peatlands can lead to misleading CF results, as the inclusion of peatland emissions is estimated to significantly increase the CF by up to multiple times, making it a critical area for mitigation efforts[49,51,52].

More targeted research on dairy farming on drained peatlands versus mineral soils is needed, to translate estimated emissions into a precise multiplier effect on milk's CF. Although CFs of drainage-based systems might significantly be underestimated, an opposite effect can be observed regarding the CF overestimation, where dairy systems do not operate on drained peatlands and carbon sequestration takes place. This highlights the importance of including site-specific soil organic carbon in life cycle inventories, to display its effect in both directions.

However, with assessing these emissions one faces various challenges: Although different approaches are available to account for soil carbon sequestration[60,76,84,95], shared consensus on one methodology is still missing, limiting the comparability of CFs[54,84,96]. This also applies to emissions from drained peat soils, that not only need to gain more attention in agricultural LCAs but also require an appropriate estimation method.

Unlike LUC, emissions, which result from a one-time event—such as from deforestation—and are allocated as 5% of the total emissions per year over a 20 year-period[96], this approach cannot be directly transferred to emissions from drained peatland. Peatland drainage does not simply result in a one-time event of emission loss but rather represents an on-going process. Therefore, emissions should be assessed on an annual basis. For yearly emission quantification of organic soils in GHG inventories Tiemeyer et al. developed a methodology, that is based on over 250 measured GHG balances in Germany[97], and that was used in the majority of studies reviewed[52,91–93]. EFs for different LU types have been developed, based on factors like water table depth and land management practices, accounting for both direct emissions from peat decomposition and indirect emissions, such as those from LUCs. According to this, drained peat soils used as grasslands emit an average of 31.7 tons of CO_2-eq per hectare per year[97]. This approach highlights the consistent relationship of water table depth and CO_2 emissions from organic soils, found in a variety of current literature: As the natural hydrological conditions get interrupted by decreasing water table depth, C emissions increase[12,48,97–102], leading to rising subsidence[103].

Demonstrating the significant influence of water table depth, the approach also emphasizes the need for accurate water table data, highlighting another great challenge that lies within the availability of primary data. Complementary application of methods, such as remote sensing, shows great potential for filling such gaps, as a rising number of studies demonstrated the assessment of LUCs, including peatlands, using satellite data[104–107]. Moreover, including model-based approaches to display complex interactions of soil properties, climatic conditions, plants etc. might help complementing simplified LCA calculations. When primary data is not available, emissions from drained peatlands should still be reported as estimates, such as provided by the IPCC, though[93,108].

The observed omission of drainage-based emissions in LCAs can, at least partly, be attributed to the tension between LCA methodology and UNFCCC (United Nations Framework Convention on Climate Change) reporting: As soil and peatland emissions fall under the LULUCF (Land Use, Land-Use Change, and Forestry) sector[109,110], which is separated from agricultural reporting, they are commonly excluded from agricultural LCAs —an omission that is inherent to the classification system itself. However, this does not justify the issue and emissions from drained peatland need to be reported taking the risk of double accounting into account.

In addition, aLCAs are widely used for benchmarking, providing a static representation of environmental impacts often based on average data, as described earlier. However, their limitations in decision-making contexts are well recognized, particularly when evaluating large-scale systemic changes, as they do not account for indirect LUCs or shifts in production that may arise from policy interventions or industry decisions[111–113]. This limitation is particularly relevant for agricultural systems, where LU dynamics and mitigation strategies, such as peatland restoration, can have cascading effects beyond direct emissions accounting[55]. While cLCAs aim to address these gaps, their application involves additional complexity and uncertainty, particularly regarding assumptions on market responses and LUC. Acknowledging these limitations is crucial when interpreting LCA results for policy and industry[112]. In the context of drained peatland emissions, their inclusion in aLCAs provide essential insights into current production-related impacts, but complementary approaches might be needed to fully capture the broader implications of LU transitions and mitigation efforts.

While this systematic literature review aimed to provide a comprehensive overview of LCA studies on dairy farming on drained peatlands in Europe, it is important to acknowledge certain limitations. The search was exclusively conducted in the Scopus database and limited to English-language, open-access peer-reviewed articles. This approach inherently carries the risk of omitting relevant studies published in other languages or in non-open-access journals. Consequently, the limited number of studies identified, particularly those explicitly conducting full LCAs on this specific topic, might reflect a research gap, but could also be influenced by these search scope limitations, potentially leading to an underrepresentation of certain regional insights within Europe.

Moreover, the focus on European countries of the present paper, where drained peat soils are mainly used for dairy production, may not fully account for the different challenges faced in other regions. In areas where peat soils are used for red meat production, forestry, or other primary land uses, allocation issues of LCAs in dairy farming might differ.

One commonly described approach to mitigate emissions from artificially drained peatlands is their rewetting to stop CO_2 release and significantly reduce ongoing C loss[114–116], which differs from active C sequestration typical of intact peatlands or certain mineral soils[117]. Rewetting also helps restore other original ecosystem functions such as improved water quality and rising biodiversity among many other benefits[114–116]. With regard to agricultural use, especially the implementation of so called "paludicultures" is suggested, where the production of biomass is still possible[118]. It has been shown that in European temperate peatlands, the rewetting of drained peatlands used for grassland are able to compensate up to 20t of CO2-eq per hectare and year by reduced CO_2 and N_2O emissions[10,48,118,119]. However, rewetting of peatlands also results in an increase of CH_4 emitted, as a negative side effect. Nevertheless, in contrast to CO_2, CH_4 represents a stronger but rather short-lived GHG[116]. Previous studies demonstrated that the effect that occurs with CH_4 emissions related to peatland rewetting does not hinder its mitigation potential in climate change in long-term consideration. Thus, it can still be considered a reliable option in agricultural LU[116,118,120]. This is supported by scientific evidence, as shown in a study of Joosten et al., that revealed the reduction of annual GHG emissions (773 t CO2-eq), N release (914 kg N), as well as a significant cooling effect (1744 kW), by rewetting a single peatland of an area of 54ha[121]. Besides, increasing biodiversity has been observed together with the colonization of key microbial communities and functional plants[121–123].

Altogether, the authors recommend including emissions from peat soils in agricultural LCAs by utilizing data from national GHG reporting under the UNFCCC framework. This approach ensures consistency with existing CO_2 and CH_4 estimates while also accounting for N_2O emissions from peat mineralization. Where applicable, national Tier 2 approaches should be used, while the IPCC Tier 1 approach for drained and rewetted organic soils (IPCC, 2014) aligned with the latest national reporting metrics should be applied where Tier 2 data are unavailable. This ensures methodological transparency and alignment with international reporting standards.

At this point, it is also important to emphasize that the suggestion of including emissions from peat soil, aims to enhance transparency for appropriate, long-term problem-solving and to assess emission inventories more comprehensively, rather than to discredit dairy farming. For sustainable mitigation strategies, it is essential to consider farmers perspectives and ensure profitability of agricultural production, thus finding holistic approaches that not only help to reduce GHG emissions, but also ensure farmers living standard and economic well-being in the long-term[62,113,118]. Therefore, solution-finding should not be considered as an individual task for landowners and farmers, but rather for society in their entirety[118,124]. Presenting a complete picture of CFs would also help to increase awareness for the environmental impact of drained peatlands in the public[51,118,124]. Recognizing the need for a fundamental shift in paradigms and agricultural standards is crucial for sustaining biomass production on agricultural peatlands.

This shift involves adopting new concepts, plant cultures and techniques[40,118,125,126], as well as necessary adjustments to policy frameworks[118]. However, also reporting mechanisms and frameworks should be critically revised. Including peat soil emissions into CF assessments would further highlight their significant environmental impact, raise awareness of these sensitive ecosystems, and emphasize their potential for ecosystem services and climate change mitigation. This, in turn, could increase societal pressure to drive necessary policy reforms.

Conclusion

Including emissions from drained peatlands is expected to significantly impact the CF of milk leading to the consideration of more comprehensive models of dairy systems, which should be part of every LCA aimed at informed decision-making[20,96,127]. Excluding fundamental emission sources from the assessment provides a distorted view on CFs, potentially limiting an appropriate development of potential mitigation strategies for combating climate change.

Against this background, this paper advocates the inclusion of emissions resulting from agricultural peatlands in LCAs and calls for standardized guidelines to improve emission inventories. In addition, the authors encourage a critical reassessment of current reporting standards and consideration of future challenges associated with their implementation.

Data availability

No datasets were generated or analyzed during the current study.

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