The International Journal of Life Cycle Assessment (2024) 29:578–596
https://doi.org/10.1007/s11367-023-02248-9

LCI METHODOLOGY AND DATABASES

Nutrient substitution for secondary fertilizer: Is current practice comprehensive enough? A review to reveal the LCA methodological challenges

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Received: 18 May 2023 / Accepted: 8 November 2023 / Published online: 27 December 2023

Abstract

Purpose As LCA is widely applied for benchmarking and decision-making, the need to clarify the ambiguity within fundamental methodological issues is imperative. Nutrient substitution, a subcategory of substitution, where credits are given for secondary fertilizer, is one of the common means to solve multi-functionality in LCA studies. This review aims to unravel the unique challenges associated with nutrient substitution, given the increasing relevance attributed to this topic.

Methods A systematic review of LCA studies available in Scopus and Web of Science (WoS) has been conducted. Studies about the recovery of nutrients from waste streams to produce fertilizer were scrutinized. As this review focuses on nutrient substitution methodology, only studies applying substitution for secondary fertilizer were included. PRISMA checklist has been used for reporting and completeness check of the review. Results are demonstrated from system modeling and explicit substitution procedure perspectives, supplemented by an investigation on sensitivity analysis.

Results and discussion As a general caveat, poor documentation and low transparency have been observed. Substitution has been used to model attributional (ALCA) and consequential LCA (CLCA) systems. The choice of functional unit combined with nutrient substitution in ALCA could attribute impacts to other functions than those studied. The determination of system boundary, especially the incorporation of the Use on Land (UoL) stage and avoided UoL emissions, is not always in accordance with the selected system modeling. Furthermore, there is no consensus on calculating the nutrient substitution rate. Single and aggregated factors comprising internal product quality, external-environmental, and external-societal variables have been identified. A prevalent observation among most studies is the absence of a sensitivity analysis pertaining to the nutrient substitution rate.

Conclusion The consistency of nutrient substitution cannot be achieved without an unambiguous definition and connotation of substitution and system modeling. The exclusion of the UoL phase not only limits the scope of a study but also fails to reflect quality differences between primary and secondary products. The key lies in elevating awareness regarding the intricacies of nutrient substitution, which consequently necessitates a rigorous definition and integration of influential factors when calculating substitutability.

Keywords Life cycle assessment · Substitution · Nutrient recycling · Methodology · System modeling · Attributional LCA · Consequential LCA

1 Introduction

1.1 Background

Fertilizer is indispensable to retain soil nutrients to assure a high crop yield and food security. Growing population intensifies the demand for production per unit of land, which is often achieved by a higher application rate of fertilizers (Stewart et al. 2005). The most commonly applied fertilizers typically contain three basic plant nutrients:

Communicated by Niels Jungbluth.

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nitrogen (N), phosphorus (P), and potassium (K) (Fertilizers Europe/IFA 2019; US EPA 2022). About 45% of collective N inputs for worldwide food production stem from synthetic fertilizers (Ladha et al. 2005). In 2019, global N fertilizer production exceeded 120 million tonnes, while both P and K fertilizers demonstrated a relatively steady production volume of 45 million tonnes (Statista 2022). On the other hand, the fertilizer industry is associated with high energy and resource intensity. Synthetic nitrogen (N) fertilizer supply chain alone accounted for over 2% of global greenhouse gas (GHG) emissions in 2018 (Menegat et al. 2022). Excessive and inefficient fertilizer application leads to eutrophication, resource depletion, and soil contamination (UNEP 2022).

One conceivable approach to facilitate sustainable development toward a circular business model within the fertilizer industry is to use alternative sources such as agricultural and municipal waste as well as wastewater to produce secondary fertilizer and soil conditioners on account of their substantial nutrient content. Nutrient recycling from waste and wastewater management not only alleviates concerns about nutrient discharge and constrained disposal alternatives but also delivers valuable products that hold the potential to improve the environmental performance of the fertilizer sector. A good example is the statutory promotion of alternative input components to produce fertilizer in the EU (Regulation (EU) 2019/1009).

Potential feedstocks for secondary fertilizer are organic matter, waste/wastewater, including certain industrial waste, and other intermediate products (e.g., digestate). Due to contaminants such as inorganic pollutants, trace elements, pharmaceuticals, and plastics, organic fertilizers such as manure are strictly regulated in many EU areas (Commission 2016). Under similar rationale, Germany advocates the phase-out of using sewage sludge as fertilizer and anchors it in new policies for further restrictions on agricultural use (German Environment Agency 2019). Additionally, an obligation of phosphorus recycling is imposed.

This cross-sector collaboration and policy development desire a comprehensive assessment tool to understand its environmental benefits and drawbacks. Life cycle assessment (LCA) is a standardized method to analyze potential environmental impacts caused by a product (good or service). By quantifying all relevant inputs and outputs of the studied system through the entire life cycle, from resource extraction to ultimate disposal, environmental hotspots and trade-offs can be identified. LCA has been broadly implemented in waste/wastewater management with a wide coverage of technologies and assessment focuses. However, analyzing nutrient recovery via LCA brings up the challenge of multi-functionality: the analyzed system provides a function of treating wastewater/waste and another function of producing a value-added fertilizer product.

ISO 140040/140044 (ISO 2006a, b) suggests a hierarchy: allocation should firstly be avoided by applying subdivision of a multi-functional process into subprocesses or system expansion, i.e., including additional functions. When allocation is inevitable through the aforementioned procedures, partitioning based on physical relationships is preferred. Issues around multi-functionality and allocation have been long discussed in the LCA community (Cederberg and Stadig 2003; Hermansson et al. 2022; Kim et al. 1997; Klöpffer 1996; Schrijvers et al. 2020; Vogtländer et al. 2001; Weidema 2000). Despite confusions around the terminology and concept, substitution and system expansion are the most commonly used approaches in the waste management sector (Heijungs and Guinée 2007; Laurent et al. 2014).

Many researchers considered substitution and system expansion commensurate (Ekvall and Weidema 2004; Tillman et al. 1994). In that regard, system expansion is considered a general principle for both approaches since the system is first expanded in either case. This is why the ILCD Handbook (EC-JRC 2010) and UNEP/SETAC Life Cycle Initiative (2011) defined substitution as a special case of the system expansion principle. However, in a narrower sense, system expansion describes adding functions to the functional unit, while substitution removes functions from the system to ensure comparability. Therefore, this study follows the understanding that substitution and system expansion are different approaches, and partially adopts the provided definition without subcategorizing substitution into system expansion, in order to establish a differentiation:

- Substitution: "Solving multifunctionality of processes by expanding the system boundaries and substituting the non-reference products with an alternative way of providing them, i.e., the processes or products that the non-reference product supersedes. Effectively, the non-reference products are moved from being outputs of the multifunctional process to be negative inputs of this process, so that the life cycle inventory of the superseded processes or products is subtracted from the system, i.e., it is credited" (UNEP/SETAC Life Cycle Initiative 2011).
- System expansion: expanding the product system to include additional functions related to the co-products (ISO 2006a, b, taking from UNEP/SETA Life Cycle Initiative 2011).

Compared to the "general" substitution, nutrient substitution (crediting the system with avoided conventional fertilizer) extends the question beyond inherent substitution rate calculation and LCA methodology, as it often involves the dynamic and complex agro-ecological system. Methodologically, nutrient substitution can be conducted either at the product (secondary fertilizer substitutes a certain fertilizer product without considering the nutrient profile) or nutrient level. This inevitably raises more challenges when identifying the avoided fertilizer because it implies stronger stress not only on the product function but also on the quality issue. The product nutrient profile, chemical form, impurity, and the receiving environment, encompassing soil, climate, and vegetation, entwine together to palpably influence fertilization performance. Furthermore, the user's perception and regulations on secondary fertilizer add more complexity to the equation.

1.2 Latest findings in nutrient substitution and motivation for this study

A sizable number of LCA case studies have been conducted to assess waste management as well as wastewater systems, two prevailing domains for nutrient recycling to produce fertilizer. Sequentially, literature reviews and theoretical discussions have been carried out with sets of specific focuses and offered individual insights on modeling nutrient recycling and substitution in LCA.

Methodological guidance in substitution has been established. Hanserud et al. (2018) have summarized three nutrient substitution principles[1] (1:1 with mineral fertilizer equivalent, maintenance, and adjusted maintenance substitution) and demonstrated how different approaches influence nutrient substitution. Vadenbo and colleagues (2017) provided a systematic structure for consistent and transparent substitution modeling for resource recovery. The substitution potential γ is defined as an end-use-specific adjustment of the avoided product in the market under the influence of supplying the co-product. As shown in the equation, $\gamma = U^{rec} \cdot \eta^{rec} \cdot \alpha^{rec:disp} \cdot \pi^{disp}$, γ is defined by four parameters: physical content of the targeted material in the recycling feedstock U^{rec}; recycling efficiency of the recyclate η^{rec}; substitutability between the secondary product and avoided product $\alpha^{rec:disp}$; and market response π^{disp}, which reflects the interaction degree of the avoided product market based on the secondary product. The first two constituents from the equation could be interpreted as recycling-technology relevant parameters that LCA modeling choices cannot exert influences. On the contrary, substitutability and market response need to be determined realistically and documented transparently. Nevertheless, there are no official frameworks or guidelines addressing nutrient substitution in sufficient detail.

A review (Laurent et al. 2014) on LCA practices in solid waste management concluded a "preferred" substitution rate of 1:1 for all "types" of substitutions. "General" substitution has also been thematically examined in the same domain (Viau et al. 2020) using the equation above (Vadenbo et al. 2017) as reviewing criteria, which conjointly offered insights regarding nutrient substitution: the most commonly adopted approach when quantifying the nutrient substitution rate is the mineral fertilizer equivalent (MFE) principle. The same finding was drawn by Brockmann et al. (2018) in the study on the agricultural use of organic residues, and a tool for determining the nitrogen MFE of organic residues and their substitutes was further developed. Reviews (Bong et al. 2017; Lam et al. 2020; Sena and Hicks 2018; Yoshida et al. 2013) have confirmed the commonality of crediting secondary fertilizer, while others (Bernstad and La Cour Jansen 2012; Diaz-Elsayed et al. 2020) identified the substantial influence of having "avoided fertilizer" on the results. Studies (Heimersson et al. 2016; Lam et al. 2020; Yoshida et al. 2013) have unveiled the fertilizer offset nutrients and their replacement ratios. However, the categorization and linkage to substitution methodology and recycling technology were not introduced. Existing work provided a foundation on nutrient substitution; nevertheless, no studies centered on nutrient substitution contextualizing with LCA methodology and substitutability calculation principle. Furthermore, across-sectoral (urban food waste, agricultural industry, and municipal wastewater system) analysis has not been conducted, which may lead to a limited understanding of nutrient substitution. While the importance of "general" substitution is being acknowledged, the intricacies of nutrient substitution have hardly been discussed.

As a less-researched area with high complexity, nutrient substitution brings challenges not only for the calculation but also for the interpretation of an LCA study. Inspired by previous studies and results, the objectives of this study, with an enlarged scope comprising all relevant sectors, are delineated as follows: (1) to systematically review LCA case studies with nutrient substitution to produce fertilizer, (2) to identify existing approaches of nutrient substitution, and (3) to pinpoint potential methodological issues/shortcomings.

2 Methods

2.1 Search strategy and screening process

A systematic literature review was conducted under the guidance of the PRISMA checklist (Page et al. 2021), which contains a set of items in review studies for reporting to reach higher completeness. The checklist is attached as Supplementary Information (SI). Combinations of keywords and their abbreviations, including *life cycle*

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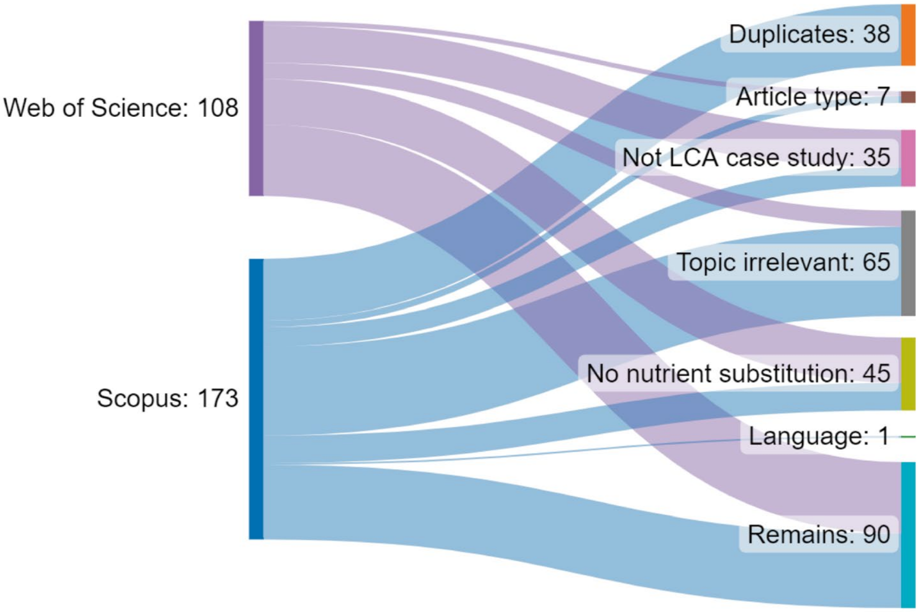
[1] One-to-one substitution: the amount of a nutrient element in mineral fertilizer equivalent (MFE) value in the secondary fertilizer can replace 100% of the correspondent element in the conventional mineral fertilizer. Maintenance substitution: a fertilization cap for each nutrient element is set. The amount of needed secondary and primary fertilizers for each element are compared. Any over-application is not given credit. Adjusted maintenance substitution: local or regional factors are integrated in the maintenance substitution. Any over-application is not given credit.

Fig. 1 Screening process of the search results. Article type indicates papers that are not journal peer-reviewed such as conference papers and theses. Category "No nutrient substitution" includes papers that give no credits for avoiding mineral fertilizer production or solve multi-functionality by system expansion or allocation



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assessment, *recycling*, *recovery*, *waste*, *sludge*, *nutrient*, *fertilizer*, and *land application*, were searched in Web of Science and Scopus. Only peer-reviewed journal articles in English available in the databases before the access date were included in this study. After removing duplicates from the search results, a rapid screening was performed by examining the title and abstract to remove irrelevant articles. A secondary screening was thereafter proceeded by applying the following criteria:

- Only case studies were taken into account. Papers that are not case study oriented but center on substitution methodological discussions (e.g., Hanserud et al. 2018) were excluded from the corpus.
- LCA case studies had to
  - encompass nutrient recycling technology producing fertilizer or fertilizer equivalence used in agriculture, which means studies with nutrient circulation back to aquaculture were excluded. Both LCA and LCI studies were incorporated. Process-based studies were included, meaning input–output and hybrid approaches were not considered.
  - consider a nutrient element that is defined and classified as macronutrients (nitrogen, phosphorus, potassium), secondary nutrients (calcium, magnesium, sulfur), and micronutrients (boron, chlorine, copper, iron, manganese, molybdenum, nickel, zinc) according to Fertilizer Europe (Fertilizers Europe n.d.) and The Fertilizer Institute (The Fertilizer Institute n.d.).
  - employ nutrient substitution, one of the approaches to solve multi-functionality. With nutrient substitution, the system is credited with avoided emissions that are associated with conventional fertilizer products. Closed-loop recycling led to exclusion as it does not provide information for the substitution methodology analysis or the choice of substituted products.
- Studies employing life cycle thinking for greenhouse gas emissions or water footprint were also included as long as credits were given due to the avoided synthetic fertilizer products.

The exact search strategy and screening process, as well as the list of complete search results, are demonstrated in SI. Figure 1 illustrates the screening process. In total, 281 search results were analyzed, and 90 articles with over 220 scenarios were included in the corpus of this study.

2.2 Literature analysis

The aim of this paper is to examine the nutrient substitution methodology, so the standard four-phase LCA analysis is not suited. Instead, criteria related to system modeling and substitution factors were used. Substitution is a multi-level procedure in which system modeling choices interact with substitution assumptions. Therefore, it is essential to analyze it from both (i) *the perspective of the overall system modeling setup* and (ii) *the specific procedure made for substitution calculation*.

Table 1 Criteria applied in this review to determine the nutrient substitution methodology

	Category	Criterion	Explanation/objective
(i) System modeling perspective	Choice of system model	ALCA CLCA	To identify the overall system setup of the LCA study and to demonstrate whether the substitution approach is applicable as a way of solving multi-functionality.
	Functional unit (FU)	Input-based FU Output-based FU	For example, input-based: to process *x* kg of input waste material; output-based: to produce *x* kg of P fertilizer using *y* recycling technology. The objective is to view whether the choice of FU is contextualized with the choice of the system model.
	System boundary	Inclusion of Use on Land (UoL) phase Inclusion of avoided emissions during the Use on Land (UoL) phase	To check the completeness regarding the avoided processes and their influence on the system boundary by combining these two criteria.
	Sensitivity analysis (SA)	Inclusion of SA SA with nutrient substitution relevant parameters	These two criteria are applied to review whether a substitution factor was considered in the SA and how significant the substitution factor impacts the overall results.

Proceeding substitution in LCA studies is highly related to the goal and scope of a study. A well-defined goal and scope of a case study are fundamental for further methodological assumptions and choices. Therefore, the ensuing criteria in Table 1 were employed to explore (i) *the overall system modeling* to map the substitution in relation to choices of system modeling, functional unit (FU), and system boundary. Additionally, sensitivity analysis was inspected in each study to outline the importance of nutrient substitution.

To analyze (ii) *the specific procedure made for substitution calculation* structurally, we applied a layered approach illustrated in Fig. 2. The first layer clarifies the workflow with 3 aspects when proceeding with nutrient substitution in LCA, namely, to identify (a) the substitution level, (b) the avoided product, and (c) the calculation of the substitution rate. Primary criteria (in hexagons) were developed for each aspect to assist a thorough analysis. The third layer consists of secondary criteria used to contextualize the primary criteria.

3 Results and discussion

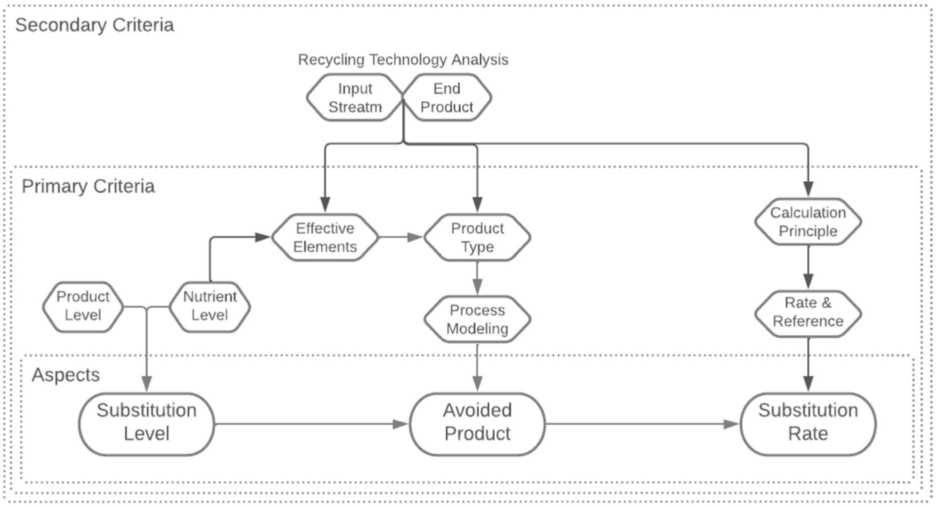
Adhering to the literature analysis structure, the findings are summarized and discussed in two major sections: 3.1 System modeling and 3.2 Substitution procedure.

3.1 System modeling

3.1.1 ALCA or CLCA

Terminology and method extension Despite the disagreement on the dichotomy in the LCA community (Suh and Yang 2014), the mainstream distinguishes LCA into two schools: ALCA and CLCA. This paper aligns with the definition of attributional and consequential LCA from Finnveden et al. (2009) due to its wide acceptance and high recognition: when a study aims to identify the share of total

Fig. 2 A layered structure for the analysis of the concrete substitution procedure. Each layer is bordered by the dotted line and the name on the left



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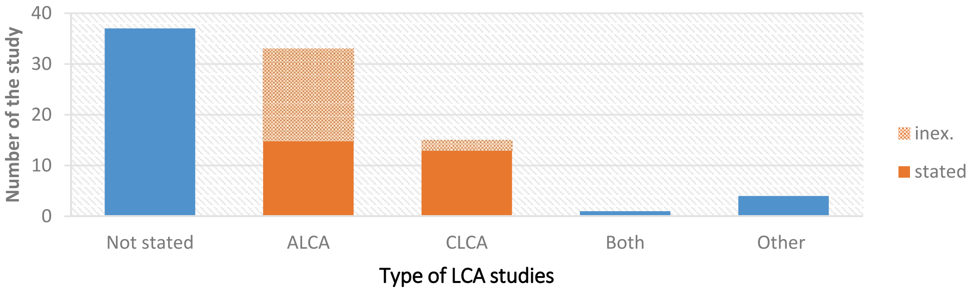

Fig. 3 Summary of LCA system modeling. Studies that are only life cycle thinking based are labeled as other, so is the water footprint study as it follows the guideline authored by WFN. Inex. denotes that the type is not explicitly stated but identified by additional criteria

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global environmental impact associated with the defined functional unit, it is classified as attributional LCA; consequential LCA is used to estimate the change in global environmental impact as a consequence of changing the demand of the functional unit (Finnveden et al. 2009).

This review used additional criteria to determine the system modeling by examining both texts and supplementary materials. Under the premise that all studies were consistently performed, consideration of background data type was used as a discerning criterion. If studies utilize, e.g., electricity supply of a market average, or ecoinvent APOS/cut-off database, it was classified as attributional LCA studies. An inexplicit statement “capture in a screenshot in time” indicated an ALCA study, while “change-oriented” classified for CLCA. Paraphrasing the research question was not used for classification, as it is usually insufficient or could be subjectively misunderstood. For example, studies aim to compare different technologies to determine the most suitable solution, yet the comparison could be made under both ALCA and CLCA settings.

Results Only 29 of the 90 reviewed papers explicitly stated the methodological choice between ALCA and CLCA (see Fig. 3). As shown, around 41% of the studies cannot be classified at all, which limits the evaluation of the substitution approach, especially at the system modeling level, as the goal definition of a study initiates the “rules” that all the methodological decisions shall follow. This result also exposes the general transparency issue in LCA studies.

Discussion Without stating the goal of the study, results might be mistakenly understood. ALCA and CLCA modeling were compared in a case study in waste management (paper 63) to demonstrate that distinct modeling setups could subsequently alter the ranking of compared alternatives. So were the outcomes of the study in other sectors, e.g., milk production (Thomassen et al. 2008). Using results from a system modeling to answer a mismatched research question presents information without scientific grounds. The conclusion from such studies might be used further as a reference for other studies or taken as examples. These results lower the value of the LCA method as an assessment measure. Therefore, a clearly defined goal and a correspondingly selected system modeling are fundamental for a valid and informative LCA study.

In light of growing emphasis on circular economy, the sophistication of end-of-life management has escalated. Advanced technologies have yielded an array of value-added products and promoted shifts in business models toward cascading material utilization. This transformation poses inevitable challenges in determining the appropriate methodology when crediting secondary materials. Applying substitution in LCA practice is not definite, primarily due to the unclear definition of terms mentioned in ISO standards and previous versions. Further official guidelines and handbooks failed to dispel ambiguity, as these documents are incompatible with each other and often with inconsistent modeling by disregarding attributional and consequential concepts (Schrijvers et al. 2016a).

The ILCD Handbook (EC-JRC 2010) promotes the application of substitution in ALCA to “include existing interactions with other systems.” In contrast, Brander and Wylie (2011) argued that introducing substitution in ALCA opposes the inclusion of actual physical burdens, as the credit in substitution comes from production that has not actually occurred. Furthermore, their argument maintained that substitution introduces consequential elements and, as such, shall not be performed in ALCA. Pelletier et al. (2015) questioned the compatibility of substitution in ALCA and criticized the inadequate representativeness of the actual system and its applicability to the ALCA paradigm. Schrijvers and co-authors (Schrijvers et al. 2016a, b, 2020) have emphasized in several publications that substitution shall not be used in ALCA.

Despite the reservations, substitution is widely used in ALCA. With the multitude of studies using substitution in ALCA, “in line with” other studies often serves as a rationale rather than a thorough methodological deliberation. Amid growing concerns and critique of substitution in ALCA, Koffler and Finkbeiner (2018) introduced a fresh angle to grasp credits derived from recycling from a holistic viewpoint where the primary burden is transferred to subsequent product cycle and reshaped through recycling activities and utilization of secondary materials, a concept termed as "embodied burden." This novel view presents an opportunity for resolving the substitution dilemma in ALCA.

However, a consensus has never been attained, marked by divergent interpretations regarding the foundational documents (ISO standards); a good example is the discussion between Finkbeiner (2021) and Heijungs et al. (2021a, b). The absence of a clear definition in ISO standards undermines the consistent interpretation of findings and the comparability across LCA studies. Using results from an ALCA study with inappropriate credits can be misleading. More critically, when lacking a nuanced understanding of substitution in ALCA, outcomes may be subject to misinterpretation. Employing such results for comparisons, especially when juxtaposed with studies that do not assign credits to their system, would only offer an incomplete narrative. Considering that ALCA is widely used for labeling schemes (Tillman 2010), such results can be misused for marketing and promotion, especially when the result turns out negative (extreme and rare case but not impossible).

Moreover, methodological discrepancies also impede the knowledge acquisition process for novice LCA practitioners, as their perspectives are frequently shaped and circumscribed by the educational origins and sources of their LCA instruction. As a result, LCA educators should be cognizant of this fact and promote critical thinking by impartially introducing different facets and dimensions of LCA, thereby fostering a dialogue-driven learning and practicing environment.

3.1.2 Functional unit

Terminology and method extension Given the objectives of a study, the chosen function is quantified as functional unit (FU), around which the entire inventory is structured. Aside from ensuring the comparability of LCA studies, a well-defined FU reflects the authors' point of view on the studied system. As discussed in several publications (Azapagic and Clift 2000; Kraus et al. 2019; Schrijvers et al. 2020), an FU can deliver information from a system or product perspective and answer different research questions. An input-based FU (e.g., hydrothermal carbonization of × kg biowaste) designates that the interest of the study is, for example, to manage a specific waste stream. On the other hand, an output-based FU (e.g., to produce × kg of bioavailable phosphorus) acknowledges the role-switching from the traditional view of a waste treatment plant to an economically value-added production.

Results Summarized in Fig. 4 (top), 67 reviewed papers opted for an input-based FU, such as "the treatment of X tonnes of sewage sludge." Twenty-one studies applied an output-based FU, among which 16 used the FU of the production of a secondary fertilizer equivalence. In total, eight studies included multiple functional units, of which five studies applied both input- and output-based functional units to assess different motives behind recycling technology and waste/wastewater treatment process. The exact formulation of FUs can be found in the SI. Furthermore, the relation between the output-based FU and system modeling is displayed in Fig. 4 (bottom).

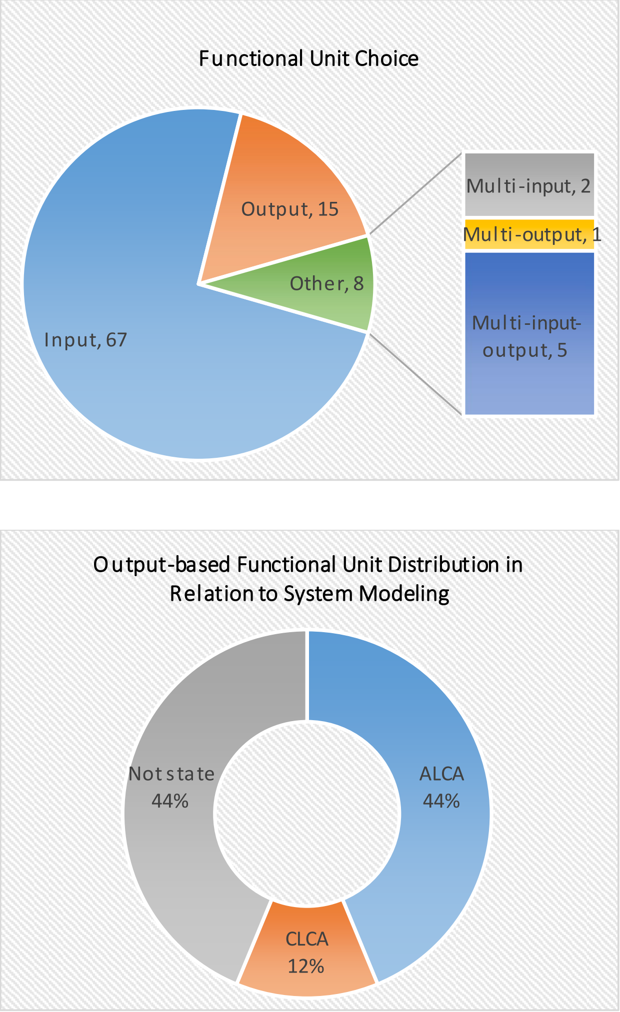

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Fig. 4 Distribution of types of functional unit (FU). ALCA and CLCA in the lower graphic include inexplicitly expressed LCI modeling type

Discussion The majority of studies employed input-based FUs, which could be interpreted as the unaltered traditional perception of waste treatment facilities despite the implementation of advanced technologies for energy and material recycling. An output-based FU might extend to the question of whether the treatment facilities become a production system. If affirmative, as suggested in the review about wastewater sludge (Pradel et al. 2016), the most widely applied "zero burden" approach is no longer suitable when sludge is supposedly considered as a "product" or "intermediate product for nutrient recycling," rather than waste.

CLCA studies can choose an output-based FU simultaneously using nutrient substitution, as a CLCA study concerns all processes that react to a change. Nevertheless, the ALCA scheme is not congruent with the same reasoning and application. For example, an ALCA case study to examine a manure treatment system via anaerobic digestion, using an FU of the production of one unit of digestate together with a nutrient substitution, is problematic. On that account, the environmental impact calculated in this study is assigned to the production of one unit digestate. Using nutrient substitution mathematically makes the system no function selected, where the results actually represent the impacts caused by producing biogas and treating manure.

As evident, this issue is fundamentally associated with system modeling. The research objective guides the formulation of FU, and the choice of FU in turn has implications for the methodology applied in addressing multi-functionality. Insufficient comprehension of the underlying meaning behind the application of substitution in ALCA may result in neglecting this interrelation.

3.1.3 System boundary

Terminology and method extension Application of substitution means to expand the system boundary from the physical technical boundary of the studied system. System boundary concerning the goal of a study encompasses the definition of investigated anthrophonic systems, time, geography, and life cycles (Tillman et al. 1994). In this section, the discussion on system boundary mainly focuses on the boundary between the technical system and the environment.

Several guidelines and frameworks are directing LCA practitioners to draw system boundaries. Three principals, namely, process tree, technological whole system, and socio-economic whole system, have been suggested to define the system boundary (Tillman et al. 1994). Ekvall and Weidema (2004) have further specified system boundaries for consequential LCA. The ILCD handbook (EC-JRC 2010) contributes several chapters for system boundary definition for attributional and consequential LCA, respectively, despite the critique on inconsistent content regarding methodological recommendations (Ekvall et al. 2016). In consequential LCA, changes happen "through the economic and technological systems in chains of cause-and-effect relations" (Ekvall and Weidema 2004), and all processes influenced by alterations in demand/consumption shall be included.

Results Fifty-nine studies, constituting 70% of the reviewed papers, incorporated the Use on Land (UoL) phase of fertilizers within their system boundary. Among these, some exclusively focused on specific aspects during the use phase, such as trace element flows or ammonia emissions. Figure 5 visualizes the distribution of studies based on their inclusion of UoL substitution, delving into the emission disparities during the use phase when applying secondary fertilizers to replace mineral fertilizers. A total of 31 studies explored UoL substitution, with nine papers, classified as CLCA or CLCA (inex.). On the other hand, there were four CLCA/CLCA (inex.) studies without engaging in UoL substitution.

Discussion Despite the controversy surrounding the practice of substitution in ALCA, our results unveiled a form of an asymmetrical "crediting" rationale. A discrepancy of nearly 10% between ALCA/ALCA (inex.) studies with and without UoL substitution brought into question the overall consistency of the approach. As for CLCA, the change in the production of secondary fertilizer triggers the adjustment in marginal conventional mineral fertilizer production. In addition, emission alteration during the use phase is also expected. As the economic system is interlaced complicatedly, it may also change the agricultural product type, machinery utilization, etc. As warned by Ekvall and Weidema (2004), it is both unattainable and meaningless to trace down every single consequence, particularly those no longer of significance and/or situated far away from the core changes. Given that nearly 60% of the total impact is attributed to field emissions (Menegat et al. 2022), investigating potential reduction by adopting alternative products is warranted.

Soil experiments have demonstrated the significant effects of fertilizer use on UoL emissions. An earlier study indicated that fertilizer type induces variation (by a factor of up to 16) in N_2O emissions (Bouwman 1996). Mineral fertilizer (e.g., urea) and secondary fertilizer (e.g., digestate, manure, compost) have demonstrated different behavior in terms of short-term and cumulative greenhouse gas fluxes (Collins et al. 2011). In a 2-year tea field experiment, controlled-release fertilizer showed around 50% lower cumulative N_2O emissions than organic fertilizer owing to disparities in water content and pH value in the products (Deng et al. 2017). Over a span of 11 years of continuous measurement, data has shown that a long-term manure application could reduce N_2O emissions compared to chemical fertilizer (Mukumbuta et al. 2017). Furthermore, impurity levels in secondary and mineral fertilizers vary significantly. Mortvedt (1996) has elucidated differences in heavy metal types and their respective concentrations in mineral and secondary fertilizers from sewage sludge. Several LCA studies (Hospido et al. 2010; Sablayrolles et al. 2010; Tarpani et al. 2020) assessing nutrient

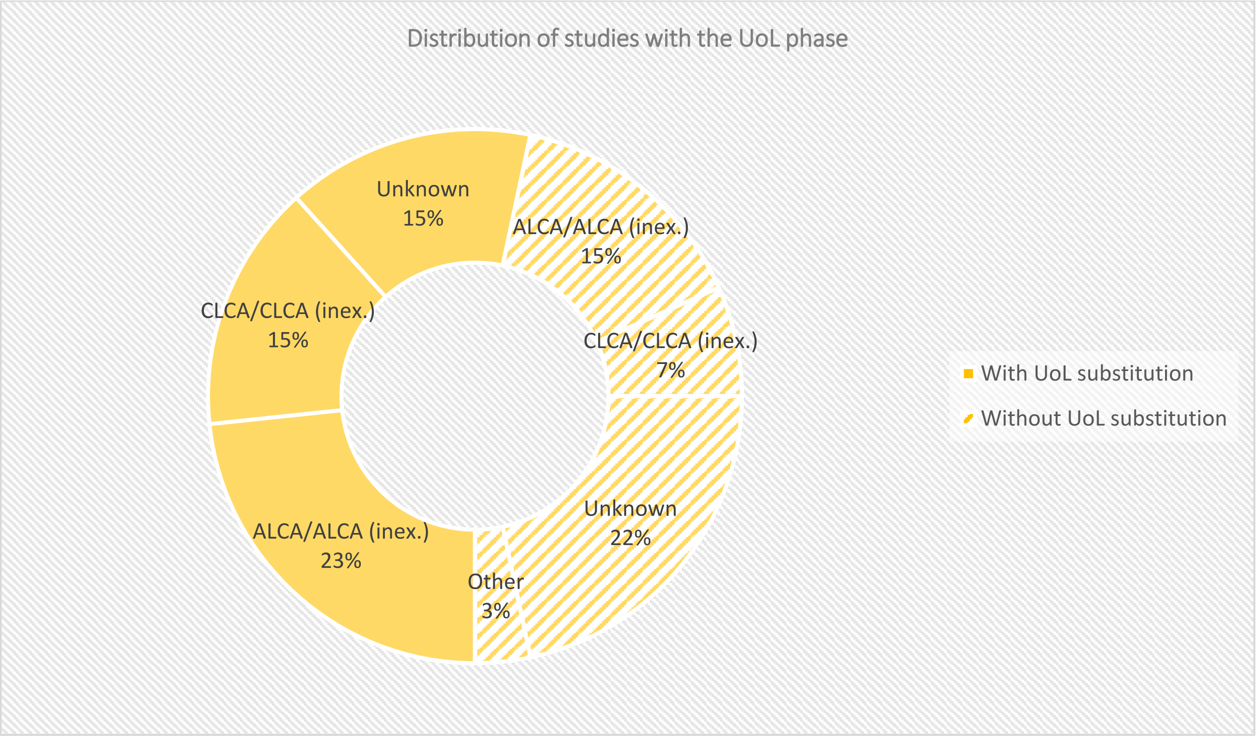

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Fig. 5 Distribution of studies incorporating the UoL phase. “Other” designates studies employing life cycle thinking-based analysis

recycling from sewage sludge indicated environmental issues caused by trace elements, including heavy metal and organic pollutants.

By including Use on Land substitution, product quality difference can be addressed, which is also the main driver for avoiding using simplified 1:1 substitution. Product quality is often understood as evaluating a product’s function by whether it serves its purpose, which is/can be integrated in the substitution rates. Yet, another conception of product quality is property, in the sense that although both primary and secondary fertilizer productions are in conformity with local regulations, trace elements, such as heavy metals, do not exhibit uniform concentration levels. This facet of product quality would be compromised if UoL emission substitution was not included. While evidence is piling up for different product quality and performance, it is not widely implemented and reflected, primarily not by employing UoL emission substitution.

Challenges when introducing UoL emission substitution are also entailed. Firstly, extra information and data on field emissions are needed. The quantification of emissions during UoL is a complex endeavor, as the agro-ecological system is highly dynamic and impossible to predict (Bouwman 1996). Many unknown factors affect the estimation of emissions due to the application of fertilizers (Mukumbuta et al. 2017). Data about UoL emissions might bring higher uncertainty to LCA modeling. Site-specific data and measurements, local ecological parameters, or computing simulations may be required to generate an inventory. Whether to incorporate UoL emissions substitution hinges significantly upon data availability and quality.

3.2 *Substitution procedure*

3.2.1 Substitution level and effective elements

Terminology and method extension One of the specialties of nutrient substitution is that it can be performed at either product or nutrient level. Product level means the secondary fertilizer is considered a complete unity that can replace another unity of fertilizer product. In this manner, the characteristics of each nutrient are disregarded, but the calculation is time-efficient and requires less information. Contrariwise, substitution can be completed at nutrient level, where each nutrient and its features, such as concentration or plant availability, are examined. By identifying each effective nutrient element that is able to achieve equivalent

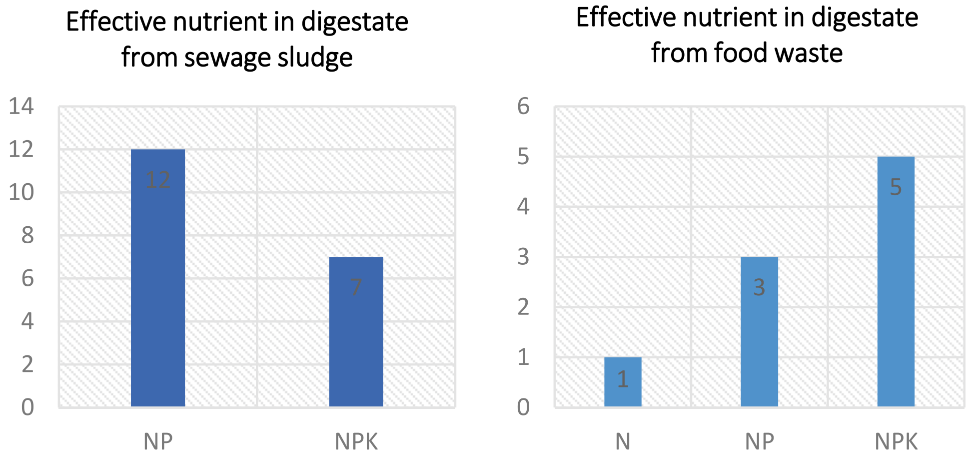

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Fig. 6 Considered nutrient element in the anaerobic digestion process for sewage sludge and food waste. N, P, and K symbolize nitrogen, phosphorus, and potassium, respectively

fertilization results as mineral fertilizer, nutrient level substitution offers a higher granularity.

Results Across all examined papers, significant parts (74 articles) of the studies conducted substitution at nutrient level, and only four papers applied substitution factor at product level. Twelve papers cannot be classified (more details in SI).

Generally, secondary nutrients, namely, magnesium and calcium, were rarely considered, appearing in only four studies with input materials including paper and pulp mill sludge, thermal residue from pulp and paper factories, power plants and municipal solid waste incineration plants, manure (pig, poultry), fruit brunches, and palm oil mill effluent. Notwithstanding the extensive spectrum of input materials sourced from agricultural and municipal contexts, the remaining studies concentrated solely on macronutrient NPK.

Anaerobic digestion (AD) is featured here as a representation to illustrate the identification of effective elements, as it is the most frequently assessed nutrient recycling technology in the corpus. The choice of effective elements of other recycling technologies can be found in the SI. Anaerobically digested municipal sewage sludge or food waste (digestate) can replace mineral fertilizer; however, the final product possesses distinct effective elements (see Fig. 6).

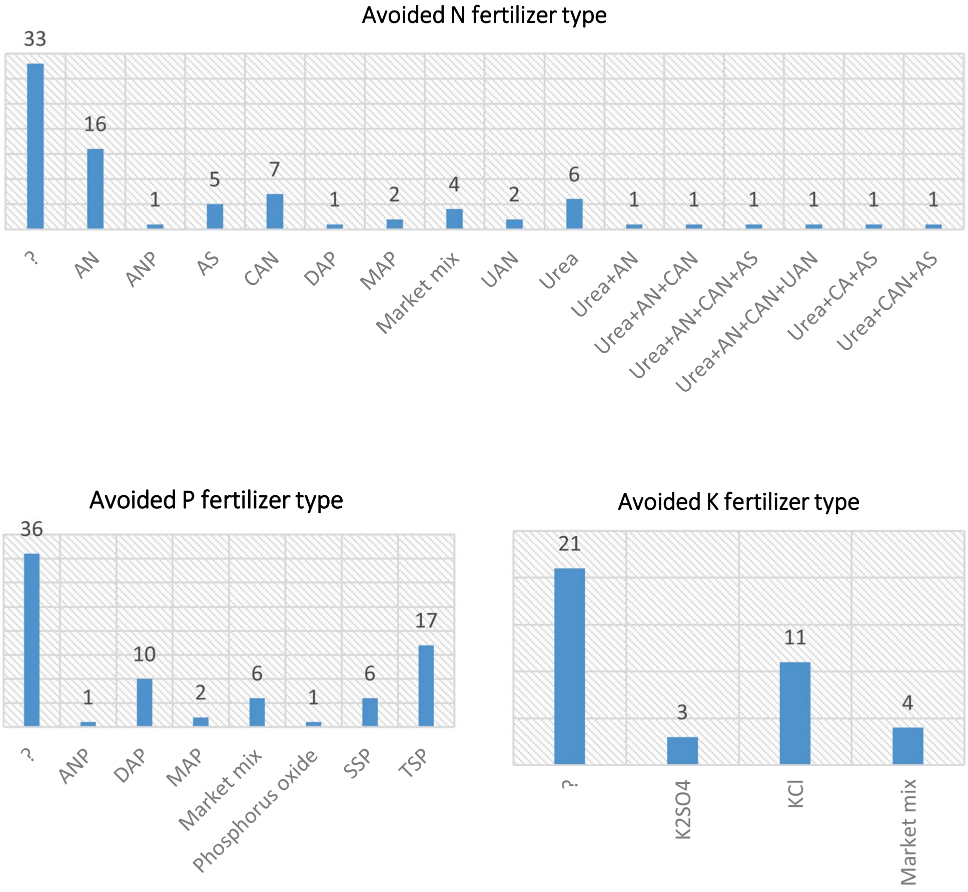
Discussion The mainstream has presented nutrient level substitution, as it offers more information about primary and secondary fertilizers and aims for higher representativeness. Another noteworthy advantage is the compatibility between substitute-substituted pairs. Many secondary products carry a non-standardized nutrient profile that does not invariably coincide with commercial fertilizer. This might lead to over- or under-estimation of the replaceability of secondary fertilizer. When conducting nutrient level substitution, nutrient profile is compartmentalized into individual effective elements, which is especially practical when comparing secondary organic and primary mineral fertilizers. However, the precondition of additional knowledge and data can result in a time-consuming process. On the other hand, product level substitution functions as a time-efficient entry strategy to test whether substitution is a hotspot and if it is a sensitive parameter.

The majority of studies focused on classical primary nutrients nitrogen (N), phosphorus (P), and K (potassium); nevertheless, no consensus has been observed in the same technology with similar input streams, or geographic regions, indicating that there is an ambiguity on effective nutrients. Drawing from the example of anaerobic digestion, this might be elucidated by the fact that nutrient concentration in sewage sludge depends highly on the characteristics of wastewater and the treatment process. When the concentration of a designated nutrient is too low in the final product, fertilizing effectiveness and hence substitution could be neglected. It might also be the constraints caused by data availability, especially when the case studies rely on public statistics. Thusly, nutrient substitution at nutrient level requires comprehensive knowledge and data on recycling technology, previous processes (not necessarily included in the system boundary), regional input material features, etc.

3.2.2 Avoided product

Terminology and method extension Once the substitution level and effective elements are established, avoided fertilizer type and production process need to be determined. Avoided fertilizer type usually corresponds to effective elements either as the same nutrient element or in the same

Fig. 7 Identified avoided product for N, P, and K, respectively. The data label indicates the amount of scenarios/papers. For more details, please refer to SI. AN: ammonium nitrate; ANP: ammonium nitrate phosphate; UAN: urea ammonium nitrate; MAP: monoammonium phosphate; CAN: calcium ammonium nitrate; CA: calcium ammonium; AS: ammonium sulfate; DAP: diammonium phosphate; SSP: single superphosphate; TSP: triple superphosphate



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chemical form. Under the context of CLCA, a 5-step procedure to identify the marginal suppliers/technologies was proposed (Weidema et al. 1999).

Results The choice of avoided products has shown great diversity. As outlined in Fig. 7, a considerable number of studies failed to provide details on avoided product type. Each nutrient element is associated with several options because determining avoided products depends strongly on regional markets and customer groups. "Market mix" data were often used for the avoided product. However, insufficient specificity within this statement renders it ineffective to distinguish, for instance, a market mix of all kinds of N fertilizers or ammonium nitrate fertilizer with all suppliers.

Discussion The credits received are highly dependent on the type of avoided product. Fertilizer industry has a rich variety of product categories and production techniques. For example, compared to the mixed-acid process, the nitrophosphate route generates less gaseous and liquid waste (Fertilizers Europe 2000). An LCA study on mineral fertilizer production (Hasler et al. 2015) has concluded that different nutrient sources and nutrient forms (e.g., urea or CAN) can affect its environmental profiles. A review examining fertilizer GHG emission factors (Walling and Vaneeckhaute 2020) has underscored a significant disparity for N and P fertilizers, attributable to differences in product typology and production geography.

Market research, in conjunction with plausible assumptions, shapes the decision to opt for substituted products. Yet, the majority of the corpus (51 out of 88 papers) relies on commercial databases such as ecoinvent or Gabi for modeling the production of avoided fertilizer, where the predominant time frame for those datasets is the late 2000s to early 2010s. When attempting to obtain up-to-date industrial data, the familiar concerns related to accessibility and transparency resurface anew. Nevertheless, existing literature has laid a solid foundation and offered references; for example, an inventory was compiled directly from two producers of DAP and MAP fertilizers (Zhang et al. 2017), and monitoring data collected at a potash fertilizer manufacturing site were contributed to the community (Chen et al. 2018).

3.2.3 Substitution rate calculation principle

Terminology and method extension Substitution rate quantifies the extent to which secondary products can supplant primary counterparts. Typically, 1:1 substitution is considered not representative and realistic (Chalmers et al. 2015). On that account, constraining factors are applied while calculating, in this case, the final mass balance for nutrient recycling. The substitution rate can consist of one or more constraining factors to reach higher representativeness of real-life cases.

In the interest of a systematic arrangement of potential constraining factors, we delineated them into three classes: internal, external-environmental, and external-societal. Internal factors suggest how fertilizer features, such as plant availability, influence the substitution rate. External-environmental factors, on the other hand, focus on the receiving environment that can affect the behaviors of fertilizer products. Variables include climate, soil condition, and crop species, which can be further sorted into subclasses such as precipitation, soil physics, and crop genotype. External-societal factors signify anthropogenic decisions such as application methods or users' preferences.

Results Following this classification, constraining factors from the reviewed studies are summarized in Table 2. Although 25 studies did not explicitly specify the calculation principle governing the avoided product quantities, the remaining studies applied at least one constraining factor. Not all studies acknowledged the fertilizing effect of secondary products. Two studies (paper 5 and 56) credited the system by using the enhanced efficiency principle, wherein the secondary product, though itself incapable of replacing mineral fertilizer directly, contributes to heightened fertilizer efficiency.

The internal factor, plant nutrient availability (PNA), stands as the most frequently employed principle across the reviewed papers. As demonstrated in the example of NPK-PNA in digestate from anaerobic digestion (AD) treating sewage sludge in Fig. 8, PNA-nitrogen varies from 24.5 to 100%. Two papers (10 and 46) differentiate the PNA values between organic and inorganic N. This distinction has also been acknowledged in another article (paper 46) on food waste management. More papers accepted 100% PNA for P and K and presented fewer fluctuations. When taking account of all scenarios disregarding the diversity of input materials and recycling technologies, the discrepancy in PNA is even more pronounced, spanning a range from 0 to 100%.

Discussion Plant nutrient availability describes (1) the percentage of a nutrient element usable for plant roots or convertible to be accessible during the growing season; (2) the contents of available nutrients in fertilizer determined by a designated method (The Soil Science Society of America, as cited in Fageria and Baligar 2004). For example, solubility of a nutrient element/product in certain solvents, such as water and citric acid, can be used as a testing method (European Parliament 2002). Integrating PNA acknowledges the difference in product quality and reflects the substitutability of the same nutrient element in various chemical configurations, which is particularly important when comparing nutrients between organic and mineral forms. The calculation based on PNA can be mathematically equal to content-based or equivalent quality calculation when PNA in both primary and secondary products is considered equal. Nevertheless, the meaning behind remains different.

A range of values has been applied for PNA. This observation aligns with the study from Kratz et al. (2014), where diverse solubility values were obtained for identical products when tested across different laboratories, primarily due to inhomogeneous production and their unstable product quality of secondary fertilizers. Other variables also play a role in introducing disparities in products manufactured via the same technology. For instance, it has been reported that P plant availability in sewage sludge varies mainly due to additive chemicals used during P precipitation (Maguire et al. 2001). Applying PNA as a constraining factor, despite the advantages, raises concern about data representativeness and data quality, as no studies explicitly declared the measurement condition of the used PNA value, and literature data are not in accordance with each other owing to technical limitations and conditions.

Aggregated constraining factors are a cluster of internal, environmental, and external factors. An example is the constraining factor mineral fertilizer equivalent (MFE), synonym of fertilizer replacement value (FRV), to showcase the replacement potential of a nutrient element in a secondary product in lieu of the same element in mineral fertilizer, all under the same predefined conditions (Jensen 2013). MFE can be either calculated with agronomic efficiency (yield-based) or fertilizer uptake efficiency, which is further affected by variables including internal, environmental, and external factors (Jensen 2013). The measurement can be performed for short term such as several weeks (Delin et al. 2012) or long term with repeated fertilizer application over years (Schröder 2005), where long-term MFE exhibited higher values (Hijbeek et al. 2018). Consequently, an analogous issue marked by a broad spectrum of values can be foreseen owing to the absence of standardized methods to measure MFE (Delin et al. 2012; Jensen 2013). Besides the technical difficulties, the value for N fertilizer in organic fertilizer is influenced by mineral N/amino N ratio (Delin et al. 2012), while P availability mainly depends on soil pH (Delin 2015).

Table 2 Constraining factors and their definitions identified from the corpus

	Internal	External-environmental	External-societal
Principle with single constraining factor	Plant nutrient availability (PNA): using the PNA of the nutrient to calculate the balance between primary and secondary products. $PNA_s \cdot C_s \cdot M_s = PNA_f \cdot C_f \cdot M_f$ Depending on the regulation, the solubility of the nutrient in different extraction agents can be used to estimate the PNA.	Soil nutrient demand: using soil nutrient demand as a threshold to calculate the needed amount of primary and secondary fertilizer.	User behavior: this indicates how willingly the user would switch to using the secondary product. The value is between 0 and 1.
	Content-based: using the nutrient concentration *C* to calculate the balance between primary and secondary products $C_s \cdot M_s = C_f \cdot M_f$		
	Enhanced efficiency: the secondary product does not possess a fertilization effect due to low plant availability. However, fertilizer efficiency is shown an improvement effect through the application of this product, which results in saving fertilizer utilization.	Crop nutrient demand: using the crop nutrient demand as a threshold to calculate the needed amount of primary and secondary fertilizer.	
	Equivalent quality: this is the 1:1 substitution assuming that the secondary product/nutrient is functionally and qualitatively equal to the primary product/nutrient.		
	Duration of fertilizer effect: using the duration of the fertilization effect to calculate the avoided primary fertilizer.		
Principle with aggregated constraining factors	Mineral fertilizer equivalent (MFE): using the MFE of the nutrient to calculate the balance between primary and secondary products. MFE indicates the replaceability of the nutrient between primary and secondary products.		Recommendation of fertilization/regulatory value
	Maintenance substitution principle (Hanserud et al. 2018): the different ratios of nutrients in the secondary product can result in an imbalanced application; that is, certain nutrients can be applied in excess than required. In such a situation, the over-application shall not be considered to substitute the mineral fertilizers.		
	Simulation models: using a model to determine nutrient fate from secondary fertilizer and mineral fertilizer. • Phosphorus life cycle inventory (Sattari et al. 2012) • Manner-NPK (Nicholson et al. 2013) • DAYCENT model (Del Grosso et al. 2005; Parton et al. 1998)		

Aggregated constraining factors indicate that several factors are taken into account within this principle

C concentration of the nutrient, *M* mass of the product, *f* primary/mineral fertilizer, *s* secondary fertilizer

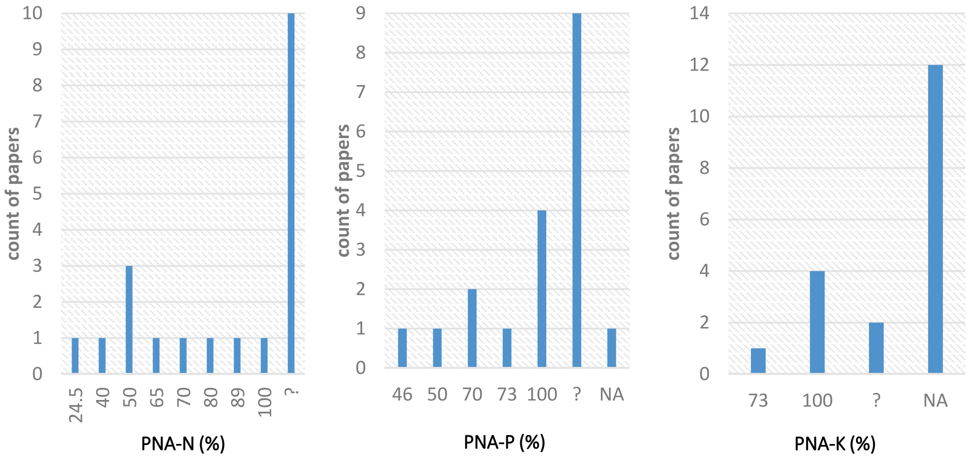

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Fig. 8 PNA of NPK from sewage sludge after anaerobic digestion treatment; NA signifies that this element is not considered as an effective nutrient to be compared to mineral fertilizer. "?" means no value was given

Leveraging agronomic simulation tools greatly facilitates the computation of the substitution rate, considering their capacity to encompass multiple relevant constraining factors and their grounding in empirical field data. Paper 16 integrated the Phosphorus Life Cycle Inventory (PLCI) model (Sattari et al. 2012) to estimate mineral P fertilizer substitution by combining MFE values with a partition rate of P within the labile soil P pool. Paper 18 used MANNER model (Nicholson et al. 2013), a simulation tool for quantifying nutrient supply from organic materials, to calculate MFE values. Similarly, paper 67 was assisted with DAYCENT model (Del Grosso et al. 2005; Parton et al. 1998) to replicate the nitrogen cycle with numerous parameters. The advantage of simulations is that influential parameters, such as local precipitation and fertilizer application method, can be coupled for higher representativeness.

The nutrient profile of multi-nutrient secondary products is highly based on the input material and the recycling technology. The content of nutrient elements often presents imbalances that are not in accordance with the soil demand/crop growth. An overestimation of avoided mineral fertilizer for such products can happen, when this is not taken into account. A practice called maintenance substitution principle (Hanserud et al. 2018) has been proposed, where excess nutrients beyond the plant demand shall not receive credits. Similar approaches comprise using soil demand or recommendation/legislation of fertilization as thresholds to prevent overestimating substitution rates. When a recycling-based product comprises more than one effective nutrient, it is of importance to identify the determined nutrient element. Illustratively, referencing paper 79, nitrogen has been selected as the determined element due to its recurring role in regulatory contexts. Consequently, any surplus of P and K exceeding the plant requirements shall not serve as a substitute for commercial fertilizer. Another possibility of overestimating the amount of avoided fertilizer is not considering the market demand. According to a study in Spain (Rufí-Salís et al. 2020), P reclaimed from wastewater surpasses regional agricultural needs by a factor of 5 to 30.

Even though regulatory values on fertilization are derived from scientific studies, aiming to effectively forestall eutrophication and simultaneously fortify food production, we assigned them as an external factor since the enforcement comes from a social-economic aspect. User behavior, which was only mentioned by two studies, implies the willingness of consumers to embrace new product offerings over established consumption patterns. Despite research findings indicating a high level of acceptance and public endorsement of secondary products (Calvo-Porral and Lévy-Mangin 2020), when it comes to fertilizer, about 30% of interviewed farmers displayed reluctance to altering from the current chemical fertilizers (Tur-Cardona et al. 2018). Therefore, gathering information about user behavior is imperative for a robust study and avoiding overestimating the substitution rate. Yet, predicting the market demand or customer preference is challenging as it involves a spectrum of factors, and such data are normally less transferable to different geographic regions.

Another observation arising from the reviewed papers is the recurring utilization of certain references for quantifying substitution rates. As mentioned in the review (Heimersson et al. 2016), a considerable amount of studies focusing on nutrient recycling in wastewater treatment invoked the reference of Bengtsson et al. (1997) and Dalemo et al. (1998) or Lundin et al. (2004) that cited back to the first two papers. This finding has been reiterated in our research. Remy and Jekel (2008), or his doctoral thesis (Remy 2010), is another commonly cited paper, where the work of Bengtsson et al. (1997) was, among others, the reference for calculating substitution rates. No other domains explored in our study were identified with such a citation trend. The determination of constraining factors shall not adhere solely to a "common" practice within the LCA community but rather align with representative rationale. LCA practitioners shall always maintain a constant awareness that the substitution rate can be subject to multi-farious regional factors, and data often fall short of being conclusive. The justification of specific assumptions shall be rigorously argued and documented, with a clear emphasis on prioritizing up-to-date data.

3.3 Sensitivity analysis

Sensitivity analysis is widely applied to grasp the sensitivity of influential parameters. As previously stated, substitution has the capacity to introduce fluctuation in final results, thus requiring a thorough investigation of the parameters around it.

As shown in Fig. 9, a significant fraction of the assessed articles featured sensitivity analysis as one of their pivotal components. However, a mere 27% of these studies examined nutrient substitution related parameters such as alternative products, substitution rate, additional effective nutrient elements, and UoL substitution (N emissions or trace element contents in the avoided product), among which about 54% of studies demonstrated a sensitive result from the tested parameters.

While nutrient substitution can exert substantial influence over LCA results, as exemplified in the study by Hanserud and colleagues (2018), the findings of this review suggest a noticeable lack of awareness and scant attention to nutrient substitution. Substitution is characterized by its multi-tiered approach with additional knowledge and underlying assumptions. Therefore, sensitivity analysis is recommended to validate those assumptions and variables.

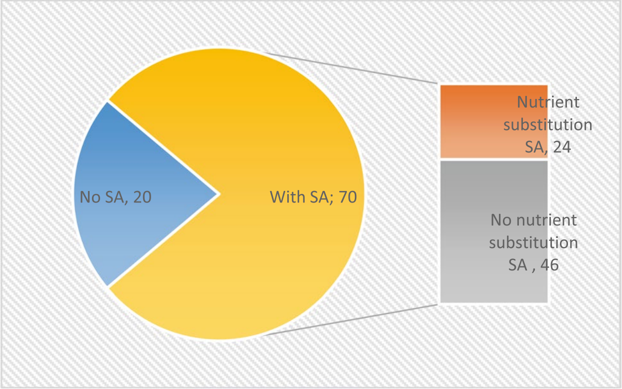

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Fig. 9 Distribution of the studies with and without a sensitivity analysis and whether the substitution rate was examined. SA: sensitivity analysis

4 Conclusion and recommendation

Transparency and documentation regarding nutrient substitution in the reviewed LCA studies have posed substantial challenges throughout the review process. Transparency is the foundation for comparison, which is one of the key features that LCA studies offer. A well-documented LCA can offer insights and direction for similar product development and provide data and guidance for further studies. In the course of analyzing the corpus, notable inquiries remained unanswered due to limited transparency. Assumptions without references and insufficient justifications have been observed. Secondary citations were also present. The aforementioned issues collectively disrupt the notion of knowledge-sharing and the fluidity of information.

The incongruity in nutrient substitution practice, on the one hand, comes from the inherent inconsistency and dissension rooted in the LCA methodology. The coherence of LCA system modeling (ALCA/CLCA) in relation to its system boundary and the consonance of multi-functionality definition are partly absent. The ISO standards, aiming to establish LCA rules and define conceptions, have not been revised for nearly 2 decades. After years of development and application, terminology has changed, acknowledged, and interpreted differently. The flexibility in LCA has become a hotbed for contradictory comprehension. In recent years, harmonization of LCA, e.g., via product category rules (PCRs) and the revision of ISO standards, are being set forth, while sector-specific guidelines and handbooks have been further developed. Thus, a multitude of interpretations and even amalgamations of approaches (such as using substitution while applying allocation factors) have emerged. Without consensual clarification in the ISO standards or the LCA community, divergent approaches to perform LCA will continue. The core challenge induced by non-unified approaches revolves around the interpretation of results to effectively convey information to product designers, stakeholders, or policymakers. The acquiescence or tolerance of those studies has devalued the LCA methodology and created room for abuse of information or even greenwashing. It also forms obstacles for individuals trying to acquire proficiency in LCA. Educators can and shall inform learners of different schools of thinking in LCA. Nevertheless, the practical implementation of methodological decisions may be guided by the frame of references received during their LCA training.

On the other hand, the intricate calculation principles add an extra level of complexity to nutrient substitution. Within the scope of our investigation, we have ascertained that a 1:1 substitution is not the preferred, and certainly not the most representative choice. Due to the dynamic feature of the agro-ecological system, more aspects and factors need to be taken into account in comparison with other product substitutions. Nutrient substitution can never fully mirror reality and a perfect substitution is virtually unattainable due to the inherent nature of modeling. Nonetheless, numerous research findings and practical applications in the agronomic domain hold the potential to significantly enhance the precision of substitutability calculations.

We summarized three types of factors from this review, namely, internal, external-environmental, and external-societal. However, the application conditions of these factors and their values vary significantly. This can result in an over- or under-estimate of avoided impacts and decreases the comparability between LCA studies. The understanding and the recognition of the specialty in nutrient substitution and its clarified methodological application need to be investigated on an ad hoc basis, as it possesses unique characteristics compared to general substitution:

- Substitution can be conducted on either product or nutrient level. At product level, both conventional and recycling-based fertilizers are compared as a whole unity, and substitution is done between two products without comparing each nutrient element contained in the product. Nutrient level indicates that the comparison is conducted based on the nutrient profile emphasizing each chemical element.
- The performance of fertilizer and its equivalent product is highly under influence of local agro-ecological system. Each case study requires a nuanced approach and a thorough analysis of regional and local variables, which encompasses an in-depth assessment of soil conditions, plantation practices, and climatic attributes. The incorporation of these factors may necessitate further modification in the LCA system, exemplified by the integration of cropping system or adaptation to the temporal boundary for crop rotation.
- Another aspect derived from the performance disparity between products is the incorporation of different life cycle stages when employing substitution. Available evidence unequivocally suggests a compelling need to investigate emission discrepancies caused by the application of different products. This deviation transpiring during the UoL phase represents a direct, traceable, and significant response within the cause-and-effect chain, a matter of pivotal importance in the context of CLCA. The consideration of whether to incorporate use phase substitution should conform to the overarching goal and scope of the study. Nonetheless, it is worth noting that a study with a bin to gate system boundary, as an example, may not be conducive to offering insights into product design and recycling technology optimization. The adoption of a consistent crediting system is imperative. When the use phase is within the system boundary, failing to include avoided UoL emissions while granting credits for avoided fertilizer production could lead to a modification of results in impact categories, notably those susceptible to soil contaminants such as trace elements.
- Imbalanced application could be induced, especially when substituting mineral fertilizer with organic fertilizer, as the variation in the ratios between nutrient elements such as N, P, or K in organic fertilizer may not match the demand exactly. This has the potential of an overapplication of particular nutrient elements. Employing a determined element as a reference can be instrumental in averting this issue.
- Whether a secondary product possesses the ability to replace mineral fertilizer, in many cases, is far from straightforward. As reported, nutrient substitution occurs even in cases where the secondary product does not exhibit a fertilization potential. By increasing the efficiency or duration of mineral fertilizing effect, savings on mineral fertilizer utilization lead to the realization of nutrient substitution.
- Effective nutrient elements in secondary products are not exclusively determined by the feedstock but also extensively contingent upon upstream processes that do not necessarily fall under the confines of the system boundary. Therefore, an exploratory analysis of processes and factors situated beyond LCA system boundary is a necessity at times.

An additional facet we want to emphasize is the notion of awareness. Researchers rarely place a primary focus on investigating the principle when calculating the substitution rate. As previously noted, substitution has not received adequate attention and the importance of sensitivity analysis with respect to substitution factors remains insufficiently acknowledged.

Last but not the least, it is noteworthy to highlight that the dissemination of interdisciplinary research findings shall be further encouraged. Infusion of knowledge and expertise from diverse domains and disciplines is imperative to enhance the quality of assumptions and interpretations in LCA studies. Nutrient substitution serves as a pertinent exemplification of this matter. Repeated reference without updated science breakthroughs makes LCA studies reluctant to deliver robust and meaningful results that are further used for communication and decision-making.

5 Limitation

This review has several limitations that constrain the comprehensiveness of the analysis. The search keyword combination does not include all the synonyms of all objects, such as biosolids. This may exclude some studies that fit our research scope. However, considering the number of reviewed papers, this research can still reflect the general situation of nutrient substitution.

As mentioned in Suh and Yang (2014), the separation of LCA into CLCA and ALCA may leave out valuable studies in between, and a continuous spectrum from idealized ALCA to idealized CLCA shall be considered. This study still follows the terminology of this dichotomy, as one aspect of the objectives of this study is to investigate how substitution is conducted and under what conditions in terms of methodological assumptions.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11367-023-02248-9.

Funding Open Access funding enabled and organized by Projekt DEAL. This work was financially supported by the German Federal Ministry of Education and Research (grant number: 02WPR1545A).

Declarations

Competing interests The authors declare no competing interests.

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