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Developing the nitrogen handprint approach to quantify the positive impacts of industrial symbiosis on nitrogen cycles

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ABSTRACT

Excessive nitrogen (N) uptake for nutrient use in food production and industry and increased N losses to the environment severely interfere with nutrient cycles and harm the environment and thus, closing N cycles through N recovery and recycling is required to improve N use efficiency. To quantify positive impacts enhancing N cycles, this study suggests a novel N handprint approach, which combines life cycle assessment based nutrient footprint and carbon handprint approaches. The N handprint comprises of a set of indicators providing a wide systemic view on changes in N cycles. The case study demonstrates that the N handprint is created when a recycled N nutrient product is used instead of a virgin N nutrient for the needs of a pulp and paper mill wastewater treatment. According to our results, the handprint equals a reduction of 454 kg of virgin N inputs, and 5.6 kg of total N inputs for daily treated wastewater. Additionally, global warming potential is 91%, and the eutrophication potential 48% lower for the recycled N nutrient than for the virgin N nutrient. These results can be used to promote the use of recycled N on similar occasions in order to improve nutrient use efficiency.

1. Introduction

Nitrogen (N) nutrients are required in large quantities, mainly as a fertilizer for the food system (Sutton et al., 2013; Kahiluoto et al., 2014). Rockström et al. (2009) and Steffen et al. (2015) stated that human activities severely interfere with global and local nutrient cycles. N resources in the atmosphere are abundant; however, the safe boundary for introducing new atmospheric N_2 to the nutrient cycle as reactive N (N_r) has been transgressed (Steffen et al., 2015) mainly due to highly inefficient use of N as a nutrient. Sutton et al. (2013) stated that, on average, over 80% of consumed N nutrient is lost to the environment. Galloway et al. (2004, 2014) defined N_r as any form of N except N_2. N_r release into the environment from the nutrient cycle takes several forms and has various adverse and sequential environmental impacts, known as the nitrogen cascade (Galloway et al., 2003). For example, the airborne emissions of greenhouse gas (GHG) N_2O accelerate climate change and NO_x emissions from combustion processes decrease air quality and cause health risks. In addition, while NO_x emissions have a negative terrestrial and aquatic eutrophication and acidification impact and damage vegetation, they also contribute to tropospheric ozone formation and harm biodiversity. Furthermore, nitrates (NO_3^-) may have a toxic impact on aquatic environments, and ammonia (NH_3) volatilization causes a deterioration in air quality (De Vries et al., 2013; Sutton et al., 2013.) The energy-intensive Haber–Bosch process to convert atmospheric N_2 to N_r accounts for 2% of global energy consumption (Sutton et al., 2013), causing further environmental impacts. A necessary solution is to increase N use efficiency by closing N cycles through nutrient recovery and recycling (De Vries et al., 2013; Kahiluoto et al., 2014).

To date, nutrient use has been mainly evaluated by using nutrient footprints and nutrient use efficiencies (Grönman et al., 2022). Many of the methods – such as the N-Calculator (Leach et al., 2012; Noll et al., 2020), the nutrient use efficiency of the full chain (Sutton et al., 2013), the N use efficiency of a food chain (Erisman et al., 2018), the N use efficiency of the life cycle (Uwizeye et al., 2016), and the N food-print (Chatzimpiros and Barles, 2013) – might be suitable for assessing food products only. More importantly, their aim is to understand the nutrient flows on a national or local scale rather than to improve the nutrient balance of a specific product system. In contrast, the nutrient footprint presented by Grönman et al. (2016) and further applied by Joensuu et al. (2019) offers a tool to identify the nutrient hotspots in bio-based product

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chains by providing a resource efficiency indicator, which focuses on the nutrient flows and nutrient balance of a system. However, the environmental impacts of nutrient emissions, such as eutrophication, are outside the scope of the nutrient footprint assessment. When necessary, combining the nutrient footprint with environmental impact indicators would give a comprehensive picture of the sustainability of nutrient use.

Nutrient footprint and nutrient use efficiency methods concentrate on assessing nutrient use but ignore the positive impacts provided by new products or solutions improving nutrient cycles. Recently, handprints have become important indicators beside footprints since they can highlight the positive environmental impacts products or services can produce (Guillaume et al., 2020). Norris et al. (2021) defined an actor's handprint "as a net positive change relative to business as usual, measurable in footprint units, of which the actor is a cause." According to Pajula et al. (2021), "a handprint refers to the beneficial environmental impacts that organizations can achieve and communicate by providing products and services that reduce the footprints of others." Grönman et al. (2019) and Pajula et al. (2018) also defined more specific carbon handprint approach to assess and communicate the positive climate impacts of products when used by a customer and compared to a business-as-usual solution. The carbon handprint approach is based on standardized life cycle assessment (LCA) methodology and utilizes footprint calculations to make the comparisons. The carbon handprint framework provides a systematic way to assess life cycle climate benefits at system level in a comparative manner. Thus, it is a useful indicator for comparing the climate impacts of different solutions and identifying improvement potential in product systems or processes. The carbon handprint approach has been applied by, for example, Jenu et al. (2020) and Kasurinen et al. (2019).

The sustainable use of nutrients is increasingly integrated into different sectors through circular economy targets (European Commission (EC), 2020). The benefits of circular solutions improving nutrient cycles have been recently discussed in the food sector by, for example, Koppelmäki et al. (2021) and Harder et al. (2021). The EC has recognized the potential for a 30% reduction of non-renewable resources in fertilizer production, and the regulation of fertilizers aims to, for example, ease the access of organic and waste-based fertilizers to the market (EC, 2016). In Finland, biowaste and biomass side-streams contained 95 000 tonnes of N annually in 2014–2016. Of this, 34 700 tonnes per year were soluble N, which could be used as a nutrient. Simultaneously, however, 152 000 tonnes of inorganic N fertilizers were used per year (Marttinen et al., 2018.) Thus, the potential for utilizing recycled nutrients is assumed to be comparatively high. As recent geopolitical instabilities have led to restricted availability of synthetic fertilizers and a steep increase in prices, the rationale for finding ways to recycle nutrients is even stronger.

Industrial symbioses play a crucial role in increasing the rate of waste and by-product circulation in industries. Besides, they may have many other benefits, including reduction of environmental impacts, GHG emissions, and the use of fossil fuels as well as creation of economic value (Fertilizers Europe, 2019). Aho et al. (2015) offered the sustainability benefits and risks of recycled nutrients produced at a biogas plant and used at an industrial wastewater treatment plant (WWTP). They concluded that the greatest sustainability benefit of nutrients results from the use of waste as a raw material instead of a virgin product. The production of a recycled nutrient product consumed less energy, water, and mineral resources than a similar product made of primary raw materials. Additionally, recycled nutrients caused lower health and environmental threats linked to chemical use (Aho et al., 2015.)

The objective of this study is to develop and test a novel N handprint approach to assess positive impacts enhancing N cycles by combining two LCA-based tools: the nutrient footprint method (Grönman et al., 2016; Ypyä et al., 2015) and the carbon handprint approach, which aims to quantify context-specific positive climate impacts (Grönman et al., 2019; Pajula et al., 2018). N footprint methodologies have concentrated on assessing absolute N flows, but they do not include assessment of potential positive impacts achieved with novel or alternative solutions. Nor do footprints enable a comparison between different solutions. The N handprint presented in this paper aims to overcome these deficiencies by providing a comparative indicator which acknowledges the real operating environment of the solutions under consideration. As is typical of handprint methodology, the benefits brought about for a user in terms of enhanced N cycles are included in the N handprint assessments. According to Zhang et al. (2020), consistent and structural multi-system and multi-spatial scale approaches with systemic-level examination to quantify nutrient budgets still lack. The N handprint approach presented in this paper aims to fill this gap by providing a systematic framework to quantify and communicate positive impacts on nutrient cycles at a systemic level. Whereas previous research has concentrated mainly on developing methods to quantify nutrient use in various food supply systems at different geographical boundaries (e.g., Chatzimpiros and Barles, 2013; Leach et al., 2016; Uwizeye et al., 2016; Erisman et al., 2018), our study aims to amplify understanding of assessing nutrient flows more widely, including in contexts other than food production.

The N handprint approach is applied and tested in a case study of an industrial symbiosis between an industrial WWTP and a provider of a recycled nutrient product to quantify the potential positive impacts on N cycles. To our knowledge, this is the first attempt to assess positive impacts on nutrient cycles by applying the handprint methodology. Previously, the handprint approach has been modified to quantify an air quality handprint (Lakanen et al., 2021) and for the use of cities and regions to quantify their positive climate actions (Lakanen et al., 2022). This study was conducted as a part of the Environmental Handprint Project by the research institution VTT and LUT University during the years 2018–2021 (Vatanen et al., 2021), and it constitutes an essential part of the extensive methodological entity of the environmental handprint introduced by Pajula et al. (2021) and Lakanen et al. (2022a).

2. Methodology

In this paper, we present an approach whereby two previously published assessment methods, the carbon handprint (Section 2.1) and the nutrient footprint (Section 2.2), are combined to form the N handprint approach. The novel N handprint approach and guidelines as to how the evaluation should be carried out are presented in Section 2.3. The N handprint approach is then applied to the case study considering N recycling as part of the needs of the WWTP of a pulp and paper mill (Section 2.4).

2.1. Carbon handprint

The carbon handprint approach provides a step-by-step procedure to assess the positive climate impacts enabled by a novel product, service, or product chain replacing a business-as-usual solution in a certain area and for certain users (Grönman et al., 2019; Pajula et al., 2018). The carbon handprint assessment compares the life-cycle carbon footprints of a baseline and a novel (i.e., offered) solution, and a handprint is created when a carbon footprint of an offered solution is less than a carbon footprint of a baseline solution. However, the key issue is that reducing own carbon footprint only is not a handprint; instead, for an offered solution to achieve a carbon handprint, it should bring about reductions in the GHG emissions of others.

A carbon handprint enables a comparison of two different products, services, or product chains. Consequently, setting a baseline essentially affects the magnitude of a potential handprint. Based on carbon handprint guidelines, a baseline should be a product, service, or product chain which delivers the same function to the user as the offered solution and is used for the same purpose by the users within a specific time period and region (Pajula et al., 2018).

2.2. Nutrient footprint

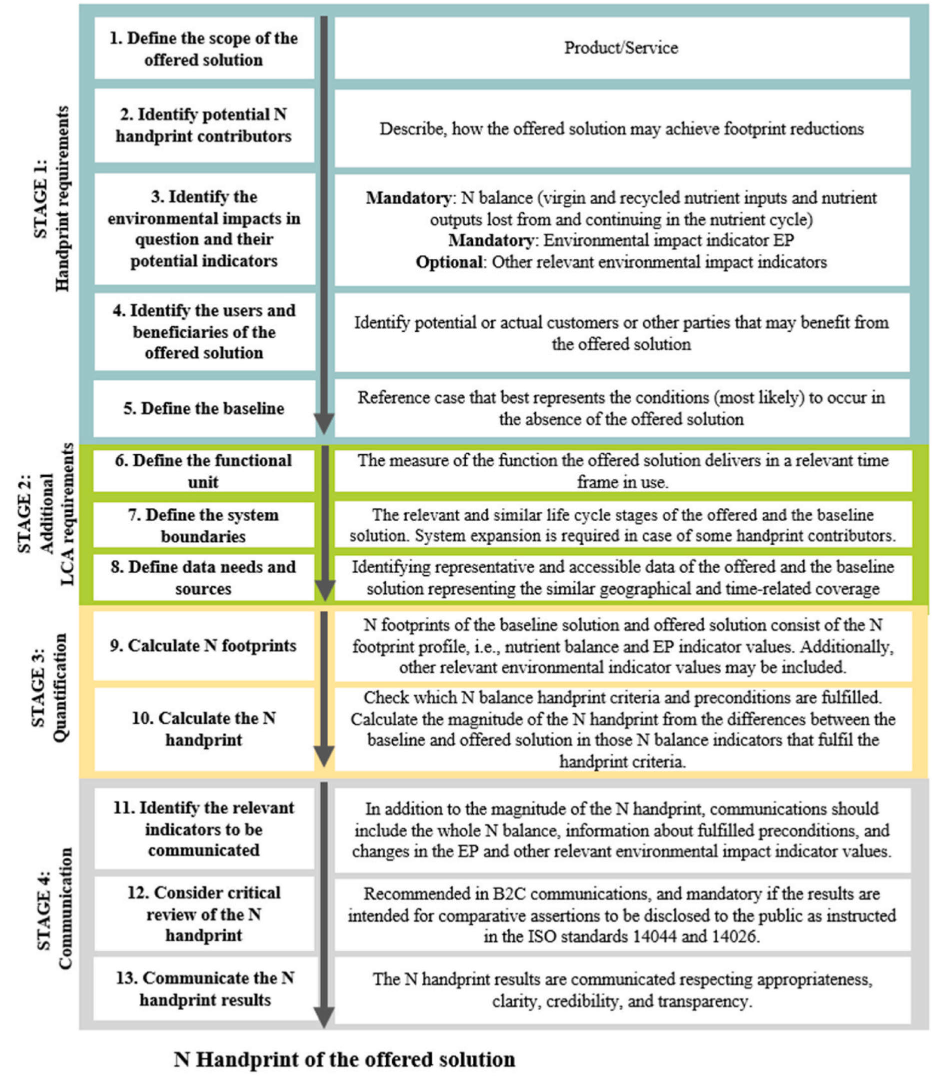
The nutrient footprint proposed by Grönman et al. (2016) is a resource efficiency indicator which focuses on nutrient flows and the nutrient balance of a system by combining nutrient intake and nutrient use efficiency. The indicator can be applied to assess the N or phosphorus (P) balances of food chains and other bio-based production chains. As based on LCA, the nutrient footprint takes into account the entire life cycle of the offered production chain. However, examination of nutrient flows is only performed at inventory level, and the amounts of nutrients are not characterized to represent different environmental impact categories.

The nutrient footprint considers virgin and recycled nutrient inputs into a system, the utilization of nutrients in product(s) of the system, and nutrient outputs as nutrient emissions, wasted nutrients, or nutrients in by-products from the system. Virgin nutrients are defined as nutrients extracted from natural resources and converted to a reactive form for human use. Recycled nutrients are already in the nutrient cycle and are recycled for human use in the system. Recycled nutrients can be, for example, waste flows or side streams whose nutrient content is further utilized. Utilized nutrients are bound to the product. Nutrients may be lost as emissions to air or water systems or as part of material that is incinerated, placed in landfill, or used for other purposes so that its nutrient content is no longer utilized for human purposes (e.g., building material) (Grönman et al., 2016).

2.3. Nitrogen handprint

This study modifies the carbon handprint approach (Grönman et al., 2019; Pajula et al., 2018) for an N context by utilizing a previously published nutrient footprint approach (Grönman et al., 2016). The N handprint approach developed is presented in Fig. 1, below. It consists of 13 steps, divided into four stages, which guide the performance of an N handprint assessment. Compared to the original carbon handprint guidelines by Pajula et al. (2018), additional steps are included in the N handprint framework (steps 1, 3, and 11), and some terms are replaced or specified to better fit the N context, especially in step 10.

The *first stage, handprint requirements*, is specific to handprint assessments, as opposed to other LCA studies (Pajula et al., 2018, 2021). In the carbon handprint assessment, the first stage includes three steps: identifying customers, identifying potential handprint contributors, and defining the baseline (Pajula et al., 2018), which requires the purpose of the N handprint assessment to be modified. First, the offered solution should be clearly specified (step 1). The offered solution refers to a product or service that can enable positive environmental impacts for its user, in this case improvement in N balance. Thereafter, potential contributors should be identified, or, in other words, a hypothesis should be made about how the offered solution could help N cycles in comparison



Stage	Step	Description
STAGE 1: Handprint requirements	**1. Define the scope of the offered solution**	Product/Service
	2. Identify potential N handprint contributors	Describe, how the offered solution may achieve footprint reductions
	3. Identify the environmental impacts in question and their potential indicators	**Mandatory**: N balance (virgin and recycled nutrient inputs and nutrient outputs lost from and continuing in the nutrient cycle) **Mandatory**: Environmental impact indicator EP **Optional**: Other relevant environmental impact indicators
	4. Identify the users and beneficiaries of the offered solution	Identify potential or actual customers or other parties that may benefit from the offered solution
	5. Define the baseline	Reference case that best represents the conditions (most likely) to occur in the absence of the offered solution
STAGE 2: Additional LCA requirements	**6. Define the functional unit**	The measure of the function the offered solution delivers in a relevant time frame in use.
	7. Define the system boundaries	The relevant and similar life cycle stages of the offered and the baseline solution. System expansion is required in case of some handprint contributors.
	8. Define data needs and sources	Identifying representative and accessible data of the offered and the baseline solution representing the similar geographical and time-related coverage
STAGE 3: Quantification	**9. Calculate N footprints**	N footprints of the baseline solution and offered solution consist of the N footprint profile, i.e., nutrient balance and EP indicator values. Additionally, other relevant environmental indicator values may be included.
	10. Calculate the N handprint	Check which N balance handprint criteria and preconditions are fulfilled. Calculate the magnitude of the N handprint from the differences between the baseline and offered solution in those N balance indicators that fulfil the handprint criteria.
STAGE 4: Communication	**11. Identify the relevant indicators to be communicated**	In addition to the magnitude of the N handprint, communications should include the whole N balance, information about fulfilled preconditions, and changes in the EP and other relevant environmental impact indicator values.
	12. Consider critical review of the N handprint	Recommended in B2C communications, and mandatory if the results are intended for comparative assertions to be disclosed to the public as instructed in the ISO standards 14044 and 14026.
	13. Communicate the N handprint results	The N handprint results are communicated respecting appropriateness, clarity, credibility, and transparency.

N Handprint of the offered solution

Fig. 1. The framework for an N handprint assessment.

to the baseline solution (step 2). In the context of N, potential handprint contributors can, for instance, lead to reductions in the use of virgin N or an increase in the use of recycled N. N recycling may also be enhanced through, for example, lower N losses from the studied system. N handprint contributors may also refer to the introduction of novel sources of recycled N or to novel use purposes of output N, such as in the case of industrial symbiosis enhancing a circular economy. New solutions and technologies may also help to optimize the use of N or prevent N losses to the environment, hence lowering environmental impacts.

In the first stage, an additional step is required in which the relevant indicators are selected and clearly indicated (step 3). As regards the indicators, it is suggested that an N handprint assessment should include two levels:

1. Assessment of changes in the **N balance** of the baseline vs. the offered solution (inventory level). As defined by Grönman et al. (2016), the nutrient balance provides information about the quantity and quality of the nutrient resources used (virgin and recycled inputs) and about the quantity of the nutrient emissions into the environment as well as the nutrients recovered for further nutrient use (the nutrient outputs lost from the nutrient cycle and continuing in the nutrient cycle).
2. Assessment of the **environmental impacts of N emissions** (impact assessment level).
   a. Mandatory: Assessment of changes in the eutrophication potential (EP) of the baseline vs. the offered solution.
   b. Optional: Assessment of other relevant environmental impact indicators. Optional indicators are selected based on assumed or identified environmental impacts related to studied solutions. For example, acidification potential may be locally important, or global warming potential (GWP) relevant as fertilizer production may be an energy-intensive process.

As the fourth step in the N handprint assessment, identifying customers requires consideration of those parties that benefit from the change in N cycles from a wider perspective (step 4). Similarly to the carbon handprint assessment (Pajula et al., 2018), an offered solution should bring about N footprint reductions for a user or beneficiary. Specification of beneficiaries is important for the inclusion of an operating environment in an assessment (Pajula et al., 2021).

Defining the baseline solution is one of the most critical steps in handprint assessment as it sets a point for a comparison (step 5). The baseline can be defined as “the reference case that best represents the conditions most likely to occur in the absence of an offered solution” (Pajula et al., 2021) and thus, it includes functions replaced by the offered solution. In general, a baseline selection depends on two fundamental questions: whether an offered solution is new on the market or replaces an existing product. In a case of the first scenario, the current situation without an offered solution is used as a baseline. The second scenario requires identifying the users of an offered solution, and if the users can be specified, their current product or another option available on the market acts as the baseline. Otherwise, the market leader or typical or average product or service in the identified area and time is chosen to be the baseline. Importantly, the baseline and the offered solution must deliver the same functions, be used for the same purpose, be available in the market, and be used in the defined time period and geographic region. An assessment must be conducted similarly for both solutions, for example in terms of data quality, system boundaries, and assumptions (Pajula et al., 2021.) These general guidelines for baseline determination in the context of a carbon handprint apply in N handprint assessment.

The *second stage, additional LCA requirements*, has three steps: defining the functional unit, defining system boundaries, and defining data needs and sources. This stage is largely based on the international standards of LCA (Pajula et al., 2018, 2021). All three steps are also essential in N handprint assessments, and the general guidelines provided in LCA standards ISO 14040 (2006) and ISO 14044 (2006) and by Pajula et al. (2018, 2021) apply in the N context. However, N handprint studies have some specific features and fundamental differences from carbon handprint studies. The climate change impact considered in a carbon handprint is global, while nutrients have a more local importance. Carbon handprints can be associated with any product or service, while N handprints are restricted to N flows, such as those related to the food system, fertilizer industry, or nutrient side streams and waste flows. Evaluating nutrient cycles may require wider system boundaries or system expansion to identify truly beneficial changes in N cycles between the offered and baseline solution.

The *third stage of the N handprint assessment requires N footprint and handprint calculations*. The greatest difference from the carbon handprint approach is that the N handprint has multiple indicators whereas carbon handprint has only one, namely CO_2-equivalent. The N footprint results, consisting of multiple indicator values, do not unambiguously indicate whether an N handprint is created and which indicators contribute to its magnitude. The basic principle of how the magnitude of the N handprint is determined is the same as for the carbon handprint: It is calculated from the difference between the N footprint indicator values of a baseline solution and the offered solution when the alternative solution is used by the same beneficiary (Grönman et al., 2019). However, clear criteria are required as to when the N handprint is created and the indicator values which determine its magnitude.

Table 1 summarizes the aspects included in the N handprint assessment as well as related N handprint criteria and preconditions. Criteria and preconditions are differentiated as follows. Criteria are related to aspects in the N balance that determine the magnitude of the N handprint. Preconditions do not affect the magnitude of the N handprint but must be fulfilled before an N handprint can be created. In other words, the N handprint means a nutrient resource handprint based on changes in the N balance (inputs and outputs) of a system. For example, the EP is used as an additional confirmation that the offered system does not adversely affect the environment; it is not used as a component of the N handprint. The N handprint is, thus, in line with the air quality handprint, which only considers changes in the mass balance of air pollutants and not, for example, midpoint environmental impacts or endpoint health impacts of air pollutants (Lakanen et al., 2021).

The N handprint is created when

- Either one or both input criteria (1, 2) are fulfilled while the output situation is at least equal in the offered solution to that in the baseline solution
- OR the output criterion (3) is fulfilled while the input situation is at least equal in the offered solution and the baseline solution
- AND the eutrophication precondition is fulfilled
- AND, if relevant, other environmental impact preconditions are fulfilled.

When determining whether the N balance allows the creation of the N handprint, the conductor of the assessment may adopt either an input or an output approach. The choice of approach may originate from identifying potential handprint contributors on the input or output side before making the calculations. For example, if a decrease in virgin N inputs in the offered solution is identified as a potential N handprint contributor, the input approach is a natural choice. Additional preconditions are needed to define the input or output situation as at least similar or equal between the baseline and offered solution. Worse situations hinder the creation of the handprint.

Supplementary materials, “N balance situations, handprint criteria, and preconditions,” describe situations in which either the input or output handprint criteria are fulfilled in combination with possible simultaneous output or input situations. These materials further describe additional N balance preconditions in each situation.

As regards the input preconditions, potential alternative uses of recycled N inputs should be included in the assessment. If more virgin N

Table 1
N handprint assessment, criteria, and preconditions. Text in italics details situations that fulfill the criteria.

N handprint assessment indicators		
N balance		**Criteria: N balance**
Mandatory	Assessment of changes in the nitrogen balance of the baseline vs. offered solution.	**INPUT CRITERIA** **1** Fewer nitrogen inputs in total are required in the offered solution than in the baseline solution. *inputs in offered solution < inputs in baseline solution* **OR 2** Virgin N inputs in the baseline solution are partly or totally replaced by recycled N in the offered solution or decreased without replacement. *virgin inputs in offered solution < virgin inputs in baseline solution* ***and*** *recycled inputs in offered solution ≥ recycled inputs in baseline solution* **Preconditions:** The output situation is better or equal in the offered solution compared to the baseline solution. Additional preconditions define equality. **OUTPUT CRITERION** **3** The ratio of the N outputs that continue in the nutrient cycle to the N outputs lost from the nutrient cycle is larger in the offered solution than in the baseline solution. The increase in the ratio must not be pursued by increasing the total amount of N inputs and outputs. *lost outputs in offered solution < lost outputs in baseline solution* ***and*** *continuing outputs in offered solution ≥ continuing outputs in baseline solution* ***or*** *lost outputs in offered solution < lost outputs in baseline solution* ***and*** *continuing outputs in offered solution < continuing outputs in baseline solution* ***and*** *the ratio of continuing to lost N is larger in offered solution than in baseline solution* ***or*** *lost outputs equal 0 in offered solution* **Preconditions:** The input situation is better or equal in the offered solution compared to the baseline solution. Additional preconditions define equality.
Environmental impacts		**Preconditions: Environmental impacts**
Mandatory	Assessment of changes in the EP of the baseline vs. offered solution.	The EP does not increase in the offered solution in comparison to the baseline solution.
Optional	Assessment of other relevant environmental impact indicators.	Other relevant environmental impact indicators do not show worse impacts in the offered solution in comparison to the baseline solution.

and less recycled N is used in the offered than in the baseline solution while total N inputs decrease, one should ensure that better uses for the recycled N justify the decrease in the ratio of recycled to virgin N in the offered solution. Similarly, when less virgin N and more recycled N is used in the offered than in the baseline solution while the total amount of N inputs is decreased, maintained, or increased, one should ensure no alternative uses for the recycled N exist. Alternative uses of recycled N in the offered solution may be included within the baseline system boundaries through system expansion. Alternative uses should be economically justified. Increasing the use of recycled N is acceptable if, for example, the recycled N is waste in the baseline solution. A further question is how better, or equal, uses should be defined and who is eligible to define uses. A general guideline, which applies well to industrial symbioses, is that using recycled nutrients that would otherwise be waste is a positive development. Otherwise, the precondition is inevitably open to discussion and discretion. A critical review of the handprint assessment adds credibility to the decision about better uses in the N handprint assessment. However, further research that leads to refining the precondition is needed.

As regards the output preconditions, first, the ratio of continuing to lost N should be at least equal in the offered and baseline solution. This might be the situation, for instance, when decrease in total N input to the system causes a decrease in both lost and continuing N outputs. In this case, decreasing the amount of N lost to the environment is a positive change, but decreasing the continuing N outputs is a negative change. However, as fewer inputs in total lead to fewer outputs in total, the negative change in continuing N should not directly hinder the handprint creation. Instead, a check should be made that the decreased total outputs are at least equally divided between the categories of continuing and lost N in the offered solution and baseline solution. For instance, if the ratio of continuing to lost N equals 0 in both the baseline and offered solution, the ratio is equal in both, and the outputs do not affect the magnitude of the handprint. Secondly, when a decrease in the total N inputs between the offered and baseline solution shows on the output side as a reduction in continuing N, the amount of lost N should equal 0 in both solutions.

Conducting an N handprint assessment and creating the assessment framework involve an iterative process. The N handprint criteria could help in stating the initial hypothesis about N handprint contributors. Some contributors set further requirements on system expansion which affect the system boundaries and baseline.

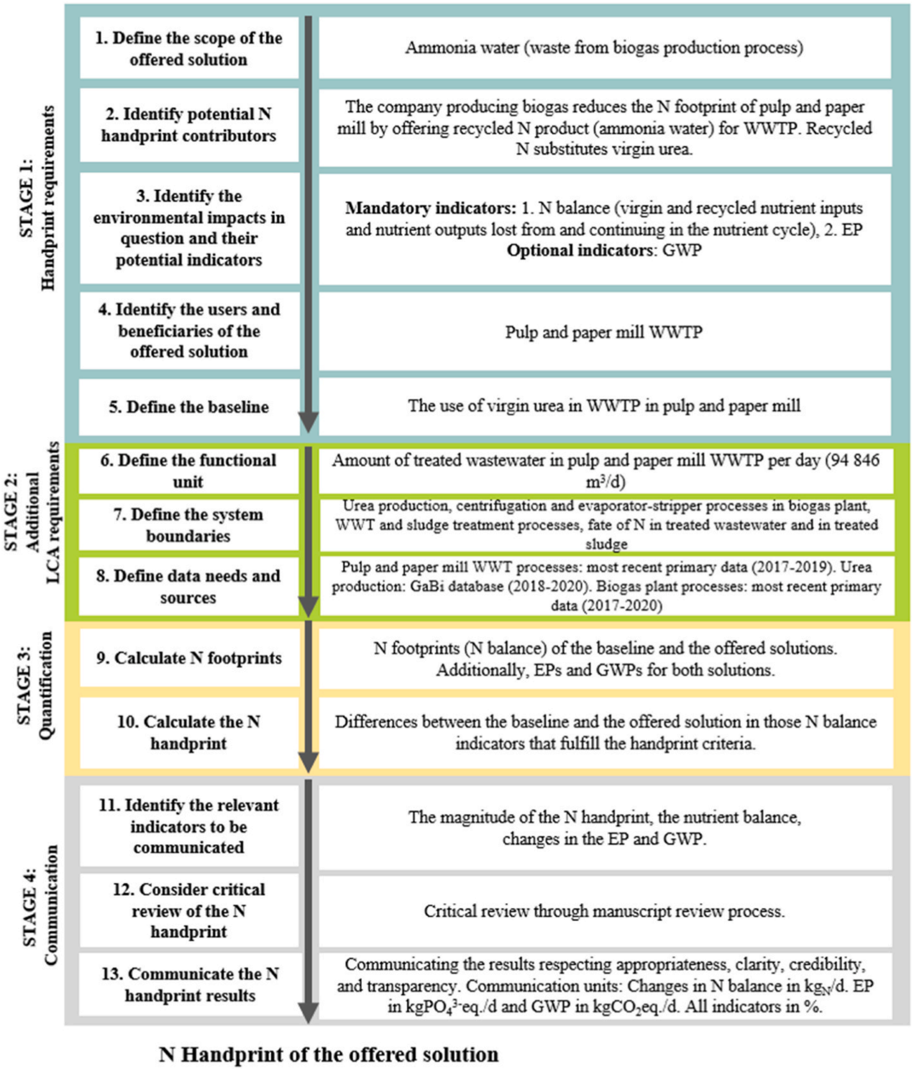
Returning to the N handprint framework, as presented in Fig. 1, the *fourth stage* deals with appropriate, clear, credible, and transparent *handprint communications*. First, it is worth identifying the relevant indicators to be communicated. In addition to the magnitude of the N handprint, communications should include the whole N balance including virgin, recycled, lost, and continuing N, as well as changes in the EP and other relevant environmental impact indicator values, preferably numerically. To be transparent, the communications should also clearly indicate, which N handprint criteria and preconditions are fulfilled, and which changes in the N balance contribute to the magnitude of the N handprint. As stated earlier, the magnitude of the N handprint is calculated from the differences between the baseline and the offered solution for those N balance indicators that fulfill the N handprint criteria (Table 1).

Second, a critical review is highly recommended, or mandatory if the results are intended to be used for a comparative assertion intended to be disclosed to the public (Pajula et al., 2018; ISO 14026; ISO 14040; ISO 14044). Appropriate and clear communication units should be used.

2.4. *Case study: recycled N nutrient product in wastewater treatment*

The presented N handprint approach was applied to the case study, which quantifies the potential beneficial impacts on nutrient cycles that can be achieved through industrial symbiosis. In the case study, the biogas plant provides a recycled N nutrient product for a pulp and paper mill WWTP to be used instead of a virgin N nutrient product. The biogas production process from biodegradable waste generates nutrient-rich digestate, which can be re-processed to N-rich ammonia water. Ammonia water can be used as a supplement N in wastewater treatment (WWT). In this case, the customer is a pulp and paper mill-activated sludge WWTP, where virgin urea is typically added to the WWT process to ensure a sufficient concentration of N.

To conduct an N handprint assessment, the N handprint framework was applied in the case study as presented in Fig. 2. The scope of the offered solution is ammonia water (step 1), which is assumed to reduce



Stage	Step	Description
STAGE 1: Handprint requirements	1. Define the scope of the offered solution	Ammonia water (waste from biogas production process)
	2. Identify potential N handprint contributors	The company producing biogas reduces the N footprint of pulp and paper mill by offering recycled N product (ammonia water) for WWTP. Recycled N substitutes virgin urea.
	3. Identify the environmental impacts in question and their potential indicators	**Mandatory indicators:** 1. N balance (virgin and recycled nutrient inputs and nutrient outputs lost from and continuing in the nutrient cycle), 2. EP **Optional indicators**: GWP
	4. Identify the users and beneficiaries of the offered solution	Pulp and paper mill WWTP
	5. Define the baseline	The use of virgin urea in WWTP in pulp and paper mill
STAGE 2: Additional LCA requirements	6. Define the functional unit	Amount of treated wastewater in pulp and paper mill WWTP per day (94 846 m^3/d)
	7. Define the system boundaries	Urea production, centrifugation and evaporator-stripper processes in biogas plant, WWT and sludge treatment processes, fate of N in treated wastewater and in treated sludge
	8. Define data needs and sources	Pulp and paper mill WWT processes: most recent primary data (2017-2019). Urea production: GaBi database (2018-2020). Biogas plant processes: most recent primary data (2017-2020)
STAGE 3: Quantification	9. Calculate N footprints	N footprints (N balance) of the baseline and the offered solutions. Additionally, EPs and GWPs for both solutions.
	10. Calculate the N handprint	Differences between the baseline and the offered solution in those N balance indicators that fulfill the handprint criteria.
STAGE 4: Communication	11. Identify the relevant indicators to be communicated	The magnitude of the N handprint, the nutrient balance, changes in the EP and GWP.
	12. Consider critical review of the N handprint	Critical review through manuscript review process.
	13. Communicate the N handprint results	Communicating the results respecting appropriateness, clarity, credibility, and transparency. Communication units: Changes in N balance in kg_N/d. EP in $kgPO_4^{3-}eq.$/d and GWP in $kgCO_2eq.$/d. All indicators in %.

Fig. 2. Framework for the N handprint approach in the case study of the recycled nutrient product in the WWTP.

the N footprint of a pulp and paper mill by offering recycled N nutrient to WWT instead of virgin urea (step 2). As a decrease in virgin N inputs in the offered solution is identified as a potential N handprint contributor, the input approach for the N handprint assessment is selected for use, as recommended in Section 2.3. According to the N handprint framework, mandatory indicators of N balance and EP are included in the assessment. Additionally, among optional indicators GWP was identified as relevant, as urea production through Haber–Bosch is highly energy-intensive (step 3). In the case study, the beneficiary is a pulp and paper mill, which needs supplementary N for its WWTP (step 4). The baseline was defined as the use of virgin urea in the WWTP (step 5). The daily quantity of treated wastewater in the WWTP (94 846 m^3) was determined to be a functional unit in a study (step 6).

Fig. 3 presents the system boundaries as well as the N and energy flows of the case study (step 7). N flows and energy consumption were examined per wastewater treated in 1 day at the WWTP, which corresponds to 94 846 m^3 wastewater. Calculations did not include biogas production because digestate from the biogas process was identified as waste. N input in wastewater from the pulp and paper mill processes was also excluded, as it is the same in the offered and baseline solutions. Transportation was included in the EP and in the GWP calculation but not in the N balance calculation. Typically, the urea used in Finland is produced in Central Europe; hence, the transportation distance was assumed to be 1300 km by ship and 100 km by truck for urea. For ammonia water, the transportation distance was assumed to be 100 km by truck. System boundaries for EP and the GWP were calculated from cradle to gate, as the customer processes were assumed to be similar in both solutions. For the N footprint, all life cycle stages from cradle to grave were included in calculations.

It was assumed that ammonia water replaces all the urea in the offered solution in a 1:1 relationship. Ammonia water is produced from digestate that is generated in the biogas production process. Digestates need to be further centrifuged, evaporated and stripped. In addition to ammonia water, N containing dry matter and NP-concentrate from centrifuged digestate are generated in the biogas plant. NP-concentrate contains P and N and can be used as a fertilizer. The energy consumption of the digestate processing was allocated to ammonia water and other N-containing outputs (sludge and NP-concentrate) based on their N masses. However, NP-concentrate was otherwise excluded from the calculations as it is not utilized in the processes described in the case study but, rather, as a separate product in other locations. The N content of biogas was assumed to be zero. As N occurs in many different forms and conversion processes are very complex, all the N was considered to be the same in the calculation.

For biogas plant and pulp and paper mill WWT processes, the most recent primary data –from the periods 2017–2020 and 2017–2019, respectively – were used. Data for urea production were secondary data from the GaBi database from the period 2018–2020 (step 8). N footprints

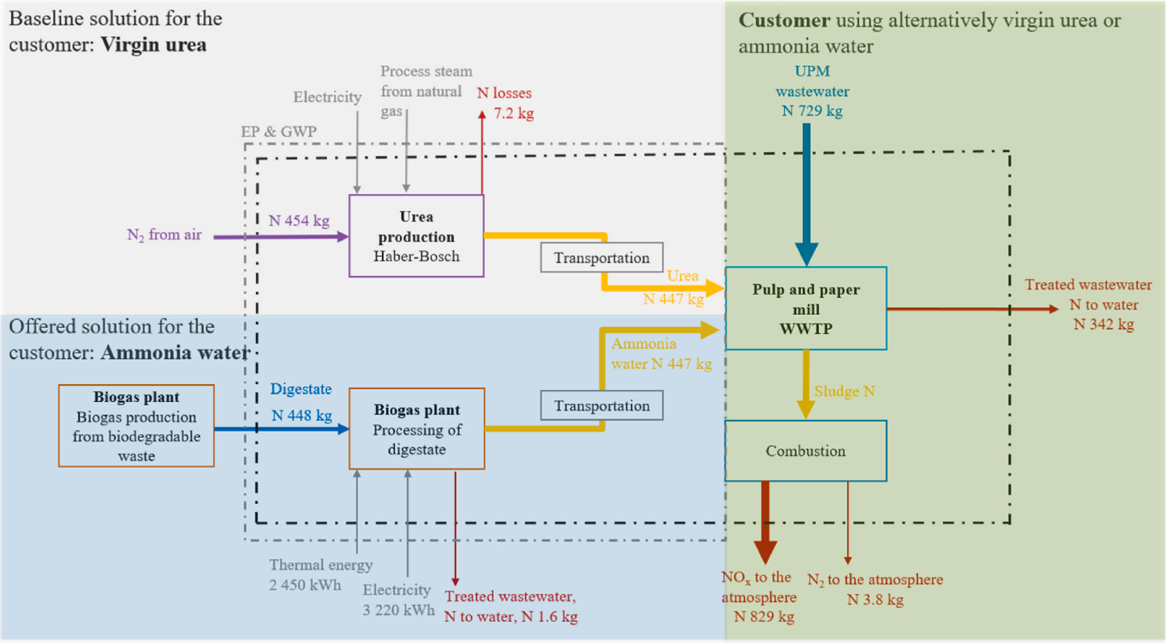


Fig. 3. System boundaries of the case study. Blue text and lines = recycled N inputs; purple = virgin N inputs; red = N outputs lost from the nutrient cycle; green = N outputs that continue in the nutrient cycle; orange = intermediate N flows; gray = energy inputs; black dashed line = system boundaries in the handprint assessment; and gray dashed line = system boundaries for the EP and GWP calculation. N masses and energy consumption are expressed per functional unit. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

for the offered and baseline solutions were calculated according to Grönman et al. (2016) (step 9). In footprint calculations, virgin and recycled N inputs, as well as the N outputs lost from the nutrient cycle and continuing in the nutrient cycle, were assessed through the life cycles of solutions. EPs for both solutions were calculated by using CML 2001 EP characterization factors, since it was assumed that both marine and freshwater may be affected. When possible, local EP characterization factors should be used. Carbon footprint calculations were conducted using a CML 2001 GWP 100-year impact analysis method with the LCA modeling software GaBi and its database (Sphera, 2019). The N handprint was calculated as the difference between the baseline and offered solutions in those N footprint indicators shown to fulfill the handprint criteria presented in Table 1 (step 10).

At the communication stage, the magnitude of the N handprint, the N balance, EP, and GWP were identified as relevant to be communicated (step 11). A critical review was assumed to be conducted through the manuscript review process (step 12). Finally, it was considered that suitable communication units for indicators would be kg_N/d for the N balance, kg phosphate equivalents/d ($kgPO_4^{3-}$eq./d) for EP, and $kgCO_2$eq./d for the GWP (step 12). Additionally, all indicators should be communicated in %.

3. Results

The N footprint for the offered and baseline solutions consists of four separate indicators: virgin N inputs, recycled N inputs, N outputs lost from the nutrient cycle, and N outputs continuing in the nutrient cycle. The total N balance of the baseline and offered solutions in kilograms of N per wastewater treated in a day at the WWTP (94 846 m^3) is presented in Fig. 4.

In the baseline solution, 453.8 kg of virgin N are needed to produce enough urea to meet the N requirements of the WWTP. Correspondingly, in the offered solution, 448.2 kg of recycled N are used for ammonia water production. The total N input is reduced by 5.6 kg_N/d in the offered solution compared to the baseline solution. This reduction fulfils the first input N handprint criterion, which states that fewer N inputs in total are required in the offered than in the baseline solution. In the baseline solution, all the N used in urea production is atmospheric N (N_2), which has been converted to a more reactive form (N_r) and can be considered a virgin nutrient. In contrast, in the offered solution, all the input N is recycled from another process (biogas production). This leads to a reduction in virgin N input of 453.8 kg/d in the offered compared to the baseline solution, which fulfills the second input N handprint criterion.

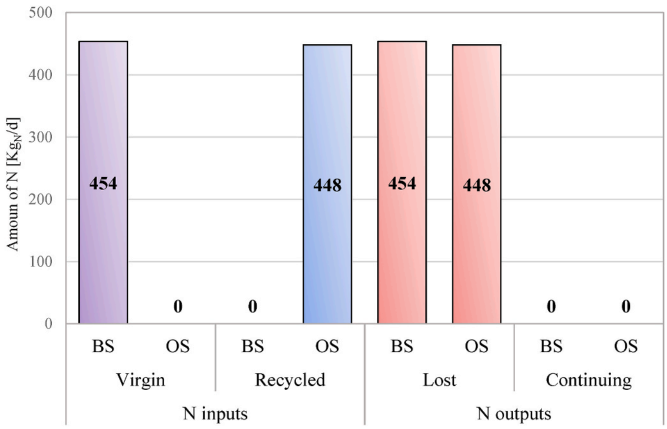


Fig. 4. N balances of the baseline and offered solutions in [kg_N/d]. BS refers to the baseline solution and OS to the offered solution.

On the output side, all the N is lost from the nutrient cycle in both solutions mainly due to the WWTP of the customer. The results show that in the baseline and offered solution, 98.4% and 99.6% of N losses occur from the WWTP, respectively. However, 5.6 kgN/d more N is lost in the baseline than the offered solution because the N input is higher in the baseline solution. In percentage terms, 1.2% less N is lost from the nutrient cycle from the offered than from the baseline solution. Due to 100% N losses in both solutions, no N continues in the nutrient cycle in either solution.

Fig. 5 presents the EP and GWP of the baseline and offered solutions as percentages. The EP of the offered solution is 48% lower than that of the baseline solution. In kilograms, the EP for the baseline is shown to be 1.76 $kgPO_4^{3-}$eq./d, while that for the offered solution is 0.92 $kgPO_4^{3-}$eq./d. Thus, in kilograms the EP is shown to be 0.84 $kgPO_4^{3-}$eq./d lower for the offered solution than for the baseline. The difference is mainly due to the renewable thermal energy used in ammonia water production, as the biogas plant uses its own biogas in heating processes. Regarding GWP, the carbon footprint for the baseline solution is 2686 kg CO_2eq./d and for ammonia water it is 256 kg CO_2eq./d. Thus, the GWP for the offered solution is 2430 kg CO_2eq./d lower than in the baseline. In percentage terms, the offered solution has a 90.5% lower lifetime GWP than the baseline.

The N handprint preconditions on environmental impacts state that the EP is not allowed to increase in the offered solution in comparison to the baseline solution. Neither are other relevant environmental impact indicators allowed to show worse impacts in the offered than in the baseline solution. As the EP and GWP are not higher in the offered than in the baseline solution, the environmental impact preconditions for the N handprint calculation are fulfilled.

In summary, the N handprint prerequisites are fulfilled in the case study, as presented in Table 2. The input approach for an N handprint assessment was observed to be suitable for the case study, according to the identified handprint contributors. In other words, in the input side, either one criterion or both criteria should be fulfilled while the output situation should remain at least equal in the offered to that in the baseline solution.

Fulfillment of N handprint criteria and preconditions indicates that the N handprint is created in the case study to the benefit of a producer of an ammonia water. The N handprint in the symbiosis between the WWTP and biogas plant equals a 5.6 kg (1.2%) reduction in total N (virgin + recycled) inputs and a 454 kg (100%) reduction in virgin N inputs due to replacement by recycled N inputs. At the same time, the N balance on the output side remains at least equal; there are no identified better uses for the recycled N that replaces virgin N, and the additional precondition on not increasing EP is met. However, even small negative changes in the nutrient balance in comparison to the current calculations could hinder the creation of the nutrient handprint.

4. Discussion

Understanding the harmful impacts of nutrients in the environment is of primary importance (Rockström et al., 2009; Steffen et al., 2015). However, as with N, previous nutrient budgeting methods do not often include impact assessment and have been criticized by the LCA community for this deficiency (Einarsson and Cederberg, 2019). LCA is a widely used tool to assess circular solutions (Corona et al., 2019; Sassanelli et al., 2019). Improvement actions on nutrient cycles, as one example of circular solutions, can be assessed with LCA. However, LCA, too, has limitations on measuring the circularity of systems (Rigamonti and Mancini, 2021). Inconsistencies have been identified in modeling open loops in LCA (Peña et al., 2021), using materials multiple times with changing material qualities requires further guidance (Haupt and Zschokke, 2017), and LCA indicators may not consider the anthropogenic stocks available (Sonderegger et al., 2020). The N handprint approach presented in this paper is LCA-compliant and includes an environmental impact assessment as well as a life cycle perspective. Besides including environmental impact categories in the context of the studied nutrients, our approach enables incorporation of nutrient origin and destination at inventory level by adapting the nutrient footprint approach. Separating the input N into virgin and recycled N improves the transparency of the assessment and allows credit to be given to recycled nutrients that are already in the anthropogenic stock and utilized multiple times.

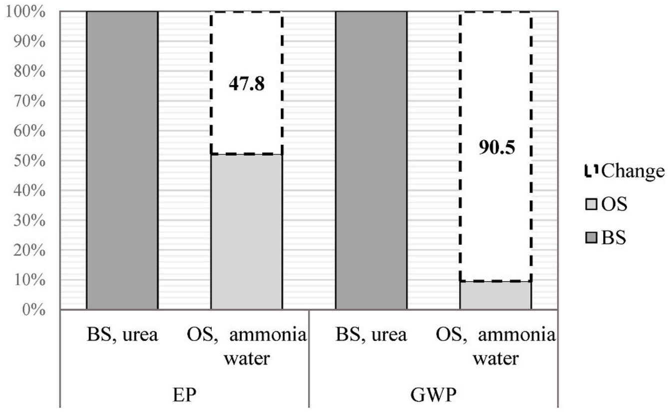


Fig. 5. EP and GWP of the baseline and offered solutions in [%]. BS refers to the baseline solution and OS to the offered solution.

Table 2
N handprint assessment, criteria, and preconditions in the case study.

N handprint assessment indicators		**Case study: Ammonia water in WWTP**
N balance		**Criteria: N balance**
Mandatory	Assessment of changes in the N balance of the baseline vs. offered solution.	**FULFILLED INPUT CRITERIA** **1.** Fewer N inputs in total are required in the offered than in the baseline solution. **2.** Virgin N inputs in the baseline solution are totally replaced by recycled N in the offered solution. **FULFILLED PRECONDITIONS:** The output situation is better in the offered than in the baseline solution.
Environmental impacts		**Preconditions: Environmental impacts**
Mandatory	Assessment of changes in the EP of the baseline vs. offered solution.	The EP does not increase in the offered solution in comparison to the baseline solution.
Optional	Assessment of GWP of the baseline vs. offered solution.	The GWP does not increase in the offered solution in comparison to the baseline solution.

According to our results concerning the case study of ammonia water, the recycled N product has the potential to reduce the N footprint of a customer, which, in this case, was a pulp and paper mill WWTP. In other words, the provider of the ammonia water thus creates an N handprint with this solution. The ammonia water provider can utilize these results in a trading situation with a potential customer to prove, on the basis of scientific fact, that environmental benefits will follow. If, for example, no environmental benefits had accrued from using the offered solution compared to the baseline product, the solution provider could have used these results to identify product or process development needs. The customer, on the other hand, can utilize these results to make informed decisions regarding their choice of N provider.

The positive nature of the results is in line with the results of Aho et al. (2015), who concluded that the greatest sustainability benefit of recycled nutrients is produced when the waste is used as a raw material in a nutrient product. Their study also found that less energy is needed to process a recycled nutrient product than that produced from virgin raw materials. In our study, this is valid as the ammonia water has minor processing needs other than transportation to the WWTP. In fact, transportation distances may become the limiting factor on the economic feasibility of the use of ammonia water. Transporting high volumes of liquid in trucks limits the potential users of ammonia water to a distance of about 100 km. Our results also indicate that ammonia water has GHG emission reduction potential of 90.5% compared to virgin urea.

The recent literature shows that reducing the environmental impacts and increasing the use efficiency of urea use are important, for example through polymer coatings (Xie et al., 2019) or Blue Urea (Driver et al., 2019).

Unlike previous nutrient indicators, the N handprint approach aims to quantify the positive impacts of products and services on N cycles based on the carbon handprint approach. As a response to a call for transparent communication with stakeholders in the field of nutrient budgeting (Zhang et al., 2020), our framework provides a novel way of messaging enhanced N cycles in business-to-customer as well as business-to-business communications. Moreover, the approach enables comparison of different products or services, indicates the need for improvements, and helps to show the most critical life cycle stages for preserving N in the cycle.

5. Conclusions and future challenges

In this article, a detailed methodological approach to calculate the positive environmental impacts of novel solutions closing, narrowing, and slowing N cycles called N handprint approach is presented. The N handprint approach was built as a combination of two existing LCA-based methods: the nutrient footprint and the carbon handprint. Then, we demonstrated the approach on a case study of the WWTP of a pulp and paper mill, which has traditionally used virgin urea to cover its N needs but could also utilize ammonia water, which is considered waste from biogas production. Our results indicate an N handprint for the ammonia water due to the daily reduction of 454 kg of virgin N inputs and 5.6 kg of total N inputs when compared to urea.

This study has applied handprinting in the nutrient context for the first time. Extending the scope of the handprint assessment from climate impacts is especially important when considering the circularity of provided solutions. Assessing only the carbon footprint of a solution may not allow some benefits of circular solutions to be brought forward, such as utilizing anthropogenic deposits available, extending the life cycle of products, or utilizing the goods multiple times.

The N handprint approach supplements existing N footprint methodologies by providing systematic guidelines to assess, at system level, positive changes occurring in N utilization throughout the life cycles of products or services. As the N handprint acknowledges the real operating environment in which the products or services are used, more realistic results can be expected than those derived from traditional LCA and footprint assessments. Additionally, the comparative character of handprinting allows diverse analyses when promoting N cycling and circular economy targets.

This study suggests that the N handprint is a suitable approach – albeit, with its multiple indicators, a laborious one – and indicator to quantify and communicate the potential positive impacts of industrial symbioses on nutrient cycles. The clear criteria and preconditions presented in this paper are needed to determine when the N handprint is created. Furthermore, creating a N handprint requires the sustainable use of nutrients and system-level nutrient balance optimization from the offered solution provider pursuing the N handprint. Our study is limited to N, but future research should include other nutrients among the handprint family as well. For example, P would be a feasible addition to the nutrient handprint approach as the calculation for the P balance is in line with that of N. However, additional environmental impact categories, such as abiotic depletion potential (ADP), should be considered in the context of P. The case study presented in this paper concentrates only on industrial symbiosis, although the applicational scope of the N handprint is much wider. Thus, further studies to test the suggested N handprint framework, criteria, and preconditions are highly encouraged in other contexts, such as the agri-food sector and for other nutrients.

CRediT author statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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References

Aho, M., Pursula, T., Saario, M., Miller, T., Kumpulainen, A., Päällysaho, M., Kontiokari, V., Autio, M., Hillgren, A., Descombes, L., Gaia, Consulting, 2015. The economic value and opportunities of nutrient cycling for Finland. Sitra Studies 104.

Chatzimpiros, P., Barles, S., 2013. Nitrogen food-print: N use related to meat and dairy consumption in France. Biogeosciences 10, 471–481. https://doi.org/10.5194/bg-10-471-2013.

Corona, B., Shen, L., Reike, D., Rosales Carreón, J., Worrell, E., 2019. Towards sustainable development through the circular economy—a review and critical assessment on current circularity metrics. Resour. Conserv. Recycl. 151, 104498 https://doi.org/10.1016/j.resconrec.2019.104498.

De Vries, W., Kros, J., Kroeze, C., Seitzinger, S.P., 2013. Assessing planetary and regional nitrogen boundaries related to food security and adverse environmental impacts. Curr. Opin. Environ. Sustain. 5, 392–402. https://doi.org/10.1016/j.cosust.2013.07.004.

Driver, J.G., Owen, R.E., Makanyire, T., Lake, J.A., McGregor, J., Styring, P., 2019. Blue urea: fertilizer with reduced environmental impact. Front. Energy Res. 7 https://doi.org/10.3389/fenrg.2019.00088.

Ec, 2016. Circular economy: new Regulation to boost the use of organic and waste-based fertilisers. European Commission. https://ec.europa.eu/commission/presscorner/detail/en/IP_16_827.

Ec, 2020. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions A New Circular Economy Action Plan for a Cleaner and More Competitive Europe. European Commission COM/2020/98 Final.

Einarsson, R., Cederberg, C., 2019. Is the nitrogen footprint fit for purpose? An assessment of models and proposed uses. J. Environ. Manag. 240, 198–208. https://doi.org/10.1016/j.jenvman.2019.03.083.

Erisman, J.W., Leach, A., Bleeker, A., Atwell, B., Cattaneo, L., Galloway, J., 2018. An integrated approach to a nitrogen use efficiency (NUE) indicator for the food production-consumption chain. Sustainability 10, 925. https://doi.org/10.3390/su10040925.

Fertilizers Europe, 2019. Circular Economy & the European fertilizer sector. https://www.fertilizerseurope.com/wp-content/uploads/2019/08/Circular_Economy_01.pdf.

Galloway, J.N., Aber, J.D., Erisman, J.W., Seitzinger, S.P., Howarth, R.W., Cowling, E.B., Cosby, B.J., 2003. The nitrogen cascade. Bioscience 53 (4), 341–356. https://doi.org/10.1641/0006-3568(2003)053[0341:TNC]2.0.CO;2.

Galloway, J.N., Dentener, F.J., Capone, D.G., Boyer, E.W., Howarth, R.W., Seitzinger, S. P., Asner, G.P., Cleveland, C.C., Green, P.A., Holland, E.A., Karl, D.M., Michaels, A. F., Porter, J.H., Townsend, A.R., Vörösmarty, C.J., 2004. Nitrogen cycles: past, present, and future. Biogeochemistry 70, 153–226. https://doi.org/10.1007/s10533-004-0370-0.

Galloway, J.N., Winiwarter, W., Leip, A., Leach, A.M., Bleeker, A., Erisman, J.W., 2014. Nitrogen footprints: past, present and future. Environ. Res. Lett. 9 (11), 115003 https://doi.org/10.1088/1748-9326/9/11/115003.

Grönman, K., Ypyä, J., Virtanen, Y., Kurppa, S., Soukka, R., Seuri, P., Finér, A., Linnanen, L., 2016. Nutrient footprint as a tool to evaluate the nutrient balance of a food chain. J. Clean. Prod. 112, 2429–2440. https://doi.org/10.1016/j.jclepro.2015.09.129.

Grönman, K., Pajula, T., Sillman, J., Leino, M., Vatanen, S., Kasurinen, H., Soininen, A., Soukka, R., 2019. Carbon handprint – an approach to assess the positive climate impacts of products demonstrated via renewable diesel case. J. Clean. Prod. 206, 1059–1072. https://doi.org/10.1016/j.jclepro.2018.09.233.

Grönman, K., Lakanen, L., Kasurinen, H., 2022. Nitrogen footprint of a food chain. In: Ren, J. (Ed.), Advances of Footprint Family for Sustainable Energy and Industrial Systems. Green Energy and Technology. Springer, Cham. https://doi.org/10.1007/978-3-030-76441-8_8.

Guillaume, J.H.A., Sojamo, S., Porkka, M., Gerten, D., Jalava, M., Lankoski, L., Lehikoinen, E., Lettenmeier, M., Pfister, S., Usva, K., Wada, Y., Kummu, M., 2020. Giving legs to handprint thinking: foundations for evaluating the good we do. Earth's Future 8, e2019EF001422. https://doi.org/10.1029/2019EF001422.

Harder, R., Giampietro, M., Smukler, S., 2021. Towards a circular nutrient economy. A novel way to analyze the circularity of nutrient flows in food systems. Resour. Conserv. Recycl. 172, 105693 https://doi.org/10.1016/j.resconrec.2021.105693.

Haupt, M., Zschokke, M., 2017. How can LCA support the circular economy?—63rd discussion forum on life cycle assessment, Zurich, Switzerland, November 30, 2016. Int. J. Life Cycle Assess. 22, 832–837. https://doi-org.ezproxy.cc.lut.fi/10.1007/s11367-017-1267-1.

ISO 14026, 2017. Environmental Labels and Declarations — Principles, Requirements and Guidelines for Communication of Footprint Information.

ISO 14040, 2006. Environmental Management - Life Cycle Assessment - Principles and Framework, 2006.

ISO 14044, 2006. Environmental Management - Life Cycle Assessment -Requirements and Guidelines, 2006.

Jenu, S., Deviatkin, I., Hentunen, A., Myllysilta, M., Viik, S., Pihlatie, M., 2020. Reducing the climate change impacts of lithium-ion batteries by their cautious management through integration of stress factors and life cycle assessment. J. Energy Storage 27 (101023). https://doi.org/10.1016/j.est.2019.101023.

Joensuu, K., Pulkkinen, H., Kurppa, S., Ypyä, J., Virtanen, Y., 2019. Applying the nutrient footprint method to the beef production and consumption chain. Int. J. Life Cycle Assess. 24, 26–36. https://doi.org/10.1007/s11367-018-1511-3.

Kahiluoto, H., Kuisma, M., Kuokkanen, A., Mikkilä, M., Linnanen, L., 2014. Taking planetary nutrient boundaries seriously: can we feed the people? Global Food Secur. 3, 16–21. https://doi.org/10.1016/j.gfs.2013.11.002.

Kasurinen, H., Vatanen, S., Grönman, K., Pajula, T., Lakanen, L., Salmela, O., Soukka, R., 2019. Carbon Handprint: potential climate benefits of a novel liquid-cooled base station with waste heat reuse. Energies 12 (4452). https://doi.org/10.3390/en12234452.

Koppelmäki, K., Helenius, J., Schulte, R.P.O., 2021. Nested circularity in food systems: a Nordic case study on connecting biomass, nutrient and energy flows from field scale to continent. Resour. Conserv. Recycl. 164, 105218 https://doi.org/10.1016/j.resconrec.2020.105218.

Lakanen, L., Grönman, K., Väisänen, S., Kasurinen, H., Soininen, A., Soukka, R., 2021. Applying the handprint approach to assess the air pollutant reduction potential of paraffinic renewable diesel fuel in the car fleet of the city of Helsinki. J. Clean. Prod. 290, 125786 https://doi.org/10.1016/j.jclepro.2021.125786.

Lakanen, L., Kumpulainen, H., Helppi, O., Grönman, K., Soukka, R., 2022. Carbon handprint approach for cities and regions: a framework to reveal and assess the potential of cities in climate change mitigation. Sustainability 14, 6534. https://doi.org/10.3390/su14116534.

Lakanen, L., Grönman, K., Kasurinen, H., Vatanen, S., Pajula, T., Behm, K., Soukka, R., 2022a. Approach for assessing environmental handprints. In: E3S Web of Conferences, vol. 349. https://doi.org/10.1051/e3sconf/202234912001.

Leach, A.M., Galloway, J.N., Bleeker, A., Erisman, J.W., Kohn, R., Kitzes, J., 2012. A nitrogen footprint model to help consumers understand their role in nitrogen losses to the environment. Environmental Development 1, 40–66. https://doi.org/10.1016/j.envdev.2011.12.005.

Leach, A.M., Emery, K.A., Gephart, J., Davis, K.F., Erisman, J.W., Leip, A., Pace, M.L., D'Odorico, P., Carr, J., Cattell Noll, L., Castner, E., Galloway, J.N., 2016. Environmental impact food labels combining carbon, nitrogen, and water footprints. Food Pol. 61, 213–223. https://doi.org/10.1016/j.foodpol.2016.F03.006.

Marttinen, S., Venelampi, O., Iho, A., Koikkalainen, K., Lehtonen, E., Luostarinen, S., Rasa, K., Sarvi, M., Tampio, E., Turtola, E., Ylivainio, K., Grönroos, J., Kauppila, J., Koskiaho, J., Valve, H., Laine-Ylijoki, J., Lantto, R., Oasmaa, A., zu Castell-Rüdenhausen, M., 2018. Towards a breakthrough in nutrient recycling: state-of-the-art and recommendations for developing policy instruments in Finland, 978-952-326-578-3. http://urn.fi/URN. (Accessed 17 November 2020).

Noll, L.C., Leach, A.L., Seufert, V., Galloway, J.N., Atwell, B., Erisman, J.W., Shade, J., 2020. The nitrogen footprint of organic food in the United States. Environ. Res. Lett. 15, 045004 https://doi.org/10.1088/1748-9326/ab7029.

Norris, G.A., Burek, J., Moore, E.A., Kirchain, R.E., Gregory, J., 2021. Sustainability health initiative for NetPositive enterprise handprint methodological framework. Int. J. Life Cycle Assess. 26, 528–542. https://doi.org/10.1007/s11367-021-01874-5.

Pajula, T., Vatanen, S., Pihkola, H., Grönman, K., Kasurinen, H., Soukka, R., 2018. Carbon handprint guide. https://www.vtt.fi/sites/handprint/PublishingImages/Carbon_Handprint_Guide.pdf. (Accessed 3 September 2020).

Pajula, T., Vatanen, S., Behm, K., Grönman, K., Lakanen, L., Kasurinen, H., Soukka, R., 2021. Carbon handprint guide v. 2.0: applicable for environmental handprint. https://www.vttresearch.com/sites/default/files/pdf/publications/2021/Carbon_handprint_guide_2021.pdf. (Accessed 30 April 2021).

Peña, C., Civit, B., Gallego-Schmid, A., Druckman, A., Caldeira- Pires, A., Weidema, B., Mieras, E., Wang, F., Fava, J., Milà i Canals, L., Cordella, M., Arbuckle, P., Valdivia, S., Fallaha, S., Motta, W., 2021. Using life cycle assessment to achieve a circular economy. Int. J. Life Cycle Assess. 26, 215–222. https://doi-org.ezproxy.cc.lut.fi/10.1007/s11367-020-01856-z.

Rigamonti, L., Mancini, E., 2021. Life cycle assessment and circularity indicators. Int. J. Life Cycle Assess. 26, 1937–1942. https://doi-org.ezproxy.cc.lut.fi/10.1007/s11367-021-01966-2.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F.S., Lambin, E.F., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H.J., Nykvist, B., de Wit, C.A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P.K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R.W., Fabry, V.J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., Foley, J.A., 2009. A safe operating space for humanity. Nature 461, 472–475. https://doi.org/10.1038/461472a.

Sassanelli, C., Rosa, P., Rocca, R., Terzi, S., 2019. Circular economy performance assessment methods: a systematic literature review. J. Clean. Prod. 229, 440–453. https://doi.org/10.1016/j.jclepro.2019.05.019.

Sonderegger, T., Berger, M., Alvarenga, R., Bach, V., Cimprich, A., Dewulf, J., Frischknecht, R., Guinée, J., Helbig, C., Huppertz, T., Jolliet, O., Motoshita, M., Northey, S., Rugani, B., Schrijvers, D., Schulze, R., Sonnemann, G., Valero, A., Weidema, B.P., Young, S.B., 2020. Mineral resources in life cycle impact assessment—part I: a critical review of existing methods. Int. J. Life Cycle Assess. 25, 784–797. https://doi-org.ezproxy.cc.lut.fi/10.1007/s11367-020-01736-6.

Sphera, 2019. GaBi Ts - Software-System and Database for the Life Cycle Engineering.

Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., de Vries, W., de Wit, C.A., Folke, C., Gerten, D., Heinke, J., Mace, G.M., Persson, L.M., Ramanathan, V., Reyers, B., Sörlin, S., 2015. Planetary boundaries: guiding human development on a changing planet. Science 347 (6223). https://doi.org/10.1126/science.1259855.

Sutton, M.A., Bleeker, A., Howard, C.M., Bekunda, M., Grizzetti, B., de Vries, W., van Grinsven, H.J.M., Abrol, Y.P., Adhya, T.K., Billen, G., Davidson, E.A., Datta, A., Diaz, R., Erisman, J.W., Liu, X.J., Oenema, O., Palm, C., Raghuram, N., Reis, S., Scholz, R.W., Sims, T., Westhoek, H., Zhang, F.S., 2013. http://www.nutrientchallenge.org/our-nutrient-world. (Accessed 9 September 2020).

Uwizeye, A., Gerber, P.J., Schulte, R.P.O., de Boer, I.J.M., 2016. A comprehensive framework to assess the sustainability of nutrient use in global livestock supply chains. J. Clean. Prod. 129, 647–658. https://doi.org/10.1016/j.jclepro.2016.03.108.

Vatanen, S., Grönman, K., Behm, K., Pajula, T., Lakanen, L., Kasurinen, H., Soukka, R., Hepo-Oja, L., Lindfors, K., Alarotu, M., 2021. The Environmental Handprint Approach to Assessing and Communicating the Positive Environmental Impacts. In: Final Report of the Environmental Handprint Project, 392. VTT Technology, 978-951-38-8752-0.

Xie, Y., Tang, L., Han, Y., Yang, L., Xie, G., Peng, J., Tian, C., Zhou, X., Liu, Q., Rong, X., Zhang, Y., 2019. Reduction in nitrogen fertilizer applications by the use of polymer-coated urea: effect on maize yields and environmental impacts of nitrogen losses. J. Sci. Food Agric. 99, 2259–2266. https://doi.org/10.1002/jsfa.9421.

Ypyä, J., Grönman, K., Virtanen, Y., Seuri, P., Soukka, R., Kurppa, S., 2015. Menetelmäkuvaus ravinnejalanjäljen laskemiseksi: laskentaesimerkkinä elintarvikeketju – NUTS-hankkeen loppuraportti. https://jukuri.luke.fi/bitstream/handle/10024/485521/luke-luobio_9_2015.pdf?sequence=1&isAllowed=y. (Accessed 10 September 2020).

Zhang, X., Davidson, E.A., Zou, T., Lassaletta, L., Quan, Z., Li, T., Zhang, W., 2020. Quantifying nutrient budgets for sustainable nutrient management. Global Biogeochem. Cycles 34, e2018GB006060. https://doi.org/10.1029/2018GB006060.