Development of circularity indicators for regional Circular Nutrient Economy (CNE) evaluation

A first attempt at integrating hierarchies, biophysical constraints, and material safety in the circularity assessment of nutrients on a regional level

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Development of circularity indicators for regional Circular Nutrient Economy (CNE) evaluation. A first attempt at integrating hierarchies, biophysical constraints, and material safety in the circularity assessment of nutrients on a regional level

Utveckling av indikatorer för cirkularitet för regional utvärdering av cirkulär näringsekonomi (CNE). En första ansats att integrera hierarkier, biofysiska begränsningar och materialsäkerhet i cirkularitetsbedömningen av näringsämnen på regional nivå

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Abstract

Circular Economy (CE) and Circular Nutrient Economy (CNE) have garnered increasing attention in both public discourse and scientific research over the past decades. The fundamental principle of CNE is to transition away from linear organic material flows by maximizing recycling and reuse while minimizing the reliance on virgin resource inputs and the disposal of unrecoverable organic waste. At the regional level, various indicators and methodologies have been developed to assess the extent to which CNE objectives are achieved, although there is yet no standardized set of indicators and neither consolidated agreement on what CNE objectives entail.

The primary aim of this study was summarizing existing literature on CNE concepts and Circularity Indicators (CIs) relevant to CNE mass flows at the regional scale. Secondly, this research sought to synthesize and operationalize CNE concepts by developing a novel framework that incorporates key CNE objectives. Lastly, the study applied newly developed indicators to assess the CNE performance of four regional systems in Europe, facilitating a comparative analysis of the actual state of CNE objectives and their circularity performance.

Despite the broad range of CNE goals identified in the literature, this study delineates three criteria for regional CNE objectives: (*1*) 4R framework, (*2*) the soil potential and biomass production limits of the region, (*3*) toxicity and regeneration at all system stages. The Phosphorus Output Circularity Index (POC_{index}) assesses *criterium 1*, ranking into classes the CNE benefits of the regions from A (high) to D (insufficient). Applied to Mass Flow Analysis (MFA) of Brandenburg, Denmark, Brussels-Capital, and Switzerland, all regions scored C, indicating rather low CNE performances. *Criterium 2* was assessed via the Standard Livestock Unit deviation (SLU_{dev}), revealing reliance on imported feed and insufficient marginal land for self-sufficiency in all four regions. *Criterium 3* was evaluated by applying the share of organic phosphorus (P) inputs, which remained low (~10%), raising concerns about organic material safety.

The POC_{index}, the organic P input share, and the SLU_{dev} indicators rely on broad assumptions, literature-derived data, and simplified mathematical formulations. While these indicators provide new qualitative insights and facilitate assessments based on readily available mass flow data, their scientific robustness remains limited and other objectives of CNE, such as import dependency, crop production, food waste reduction & reuse, or environmental impact, remain unaddressed. A key challenge identified in this study is the multidimensional nature of CNE concepts, which encompasses social, economic, global, and environmental dimensions. Future research should focus on identifying the most effective metrics and standardizing CNE evaluation methodologies to enhance the reliability and comparability of regional circularity assessments.

Keywords: Circular Economy (CE), Circular Nutrient Economy (CNE), CNE objectives, Circularity Indicators (CIs), regional circularity assessments, Mass Flow Analysis (MFA), POC_{index}, SLU_{dev}, share of organic P input

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Abbreviations

AD	Anaerobic digestion
C	Circularity
CE	Circular economy
CEAP	Circular economy action plan
CI	Circularity indicator
CNE	Circular nutrient economy
EMF	Ellen MacArthur foundation
FL	Food loss
FLW	Food loss and waste
FSC	Food supply chain
FW	Food waste
HM	Heavy metals
IC	Input circularity
LCA	Life cycle assessment
LFI	Linear flow index
LP	Livestock production
MCI	Material circularity indicator
MFA	Material flow analysis
MSW	Municipal solid waste
N	Nitrogen
OB	Objective
OC	Output circularity
P	Phosphorus
POC_{index}	P output circularity index
RR	Recycling rate
SB	System boundary
SLU	Standard livestock unit
WH	Waste hierarchy
WWTP	Wastewater treatment plant

1. Introduction

Natural resources are being exploited by increasing trends of linear material flows, raising serious global concerns about the security of and access to natural resources for future livelihoods (EEA, 2016). Circular Economy (CE) is a broader concept that includes environmental, societal, and economic dimensions. (Kirchherr, et al., 2017). Beside the fact that the goals of CE are politically and socially ambitious, scientific research on CE remains in its infancy (Korhonen et al., 2018).

Circular economy has great potential to reduce pressure on natural resources (Haas et al., 2015). The circular nutrient economy (CNE) is a growing field of studies as well, the goal of which is to achieve a transition from the use of virgin nutrients to nutrient recycling from residues that have been removed from the environment by agriculture (Valve et al., 2020).

Globally, the extraction, processing and disposal of biological materials is a major source of greenhouse gas emissions, water stress and biodiversity loss (European Commission, 2020). In a business-as-usual scenario, future global material consumption and waste generation rates are set to more than double in the next forty years (EC, 2020).

In Europe, certain types of sewage sludge, manure, and digestates are already used as recycled fertilisers and these products are supported by consolidated regulations for the use in agriculture (Krause, et al., 2021). However, for example in Germany, most of the sludge from wastewater treatment plants (WWTP) exceeds threshold values of various heavy metals like cadmium (Linderholm et al., 2012), and is therefore incinerated (Theobald, et al., 2016). Additionally, currently there are no regulations for fertilisers produced from source-separated human excretions in Europe, which is inhibiting the development into practice of nutrient recycling even though processes, technology and good-practice examples are available in research and pilot projects (Krause, et al., 2021).

A major problem for the field of circular economy, as well as for the circular nutrient economy, is that these are concepts with unclear definitions and assessment metrics. Additionally, there are other competing concepts such as bio-based economy, green economy, or circular bioeconomy, which overlap the contents and objectives of CNE (Kardung et al., 2021).

For decades, nutrient leakages have caused eutrophication and global trade of agricultural goods led to nutrient depletion in net exporter countries and accumulation in net importers (Buckwell & Nadeu, (2016); Harder, et al., (2021)). In European countries manure, municipal waste streams and food processing waste (particularly from slaughterhouses) are the three largest substrates with high potential for nutrient recovery (Buckwell & Nadeu, 2016). It is estimated that if these substrates were optimally recovered, they could cover 18-46% of the total N and 43% of the total P applied to EU crops (Buckwell & Nadeu, 2016).

Circular economy operates on many levels, including products, companies, cities, and nations (Kirchherr et al., 2017). To counter the issues of linear economic systems, the EU wants to address sustainability goals by implementing the Circular Economy Action Plan (CEAP) (European Commission, 2020). While initiatives such the CEAP are increasing in the business and policy sectors, scientific research on circular economy remains underexplored (Korhonen et al., 2018).

1.1 Specific problems addressed

In the area of pollution prevention, waste management and agricultural production, several mass flow analysis (MFA) studies with their related circularity indicators exist (Harder et al., 2021; Koppelmäki et al., 2021; Papangelou et al., 2021). In system analysis nutrient flows can be mapped to figure trends in environmental pressures or waste generation. MFA is an efficient tool that helps to understand, among other things, the sources, recyclability, or disposal of materials (OECD, 2008).

Circularity indicators (CIs) are understood as a group of indicators among many others that belong to the umbrella term of circular economy indicators (Moraga et al., 2019), which can be on different levels of analysis and include social and economic aspects as well. Especially indicators to measure CNE performances are of various type, difficult to apply and not standardized (Moraga et al., 2019), since each study developed their own indicators, or the indicators are based on different objectives and criteria. For these reasons, in the scientific domain, a crucial challenge seems to be agreeing on a standardised set of circularity indicators (CIs) to measure the progress towards the goals of CE (Moraga et al., 2019). As an example, the Swiss circularity gap report (2023) explicitly states that circularity metrics of the ecological cycling potential of the biomass have been excluded from their circular economy assessment, because of lacking tools to measure nutrient circularity (Circle Economy, 2023). Likewise, Haas et al. (2020) analyse the global socioeconomic circularity of biomass only by considering the carbon neutrality of flows.

The authors suggest that additional assessments such as disruption of biogeochemical cycles, soil erosion, fertiliser application, and nutrient emissions should be integrated (Haas et al., 2020). Nutrient flows studies are in some cases assumed to be circular by nature, without considering for example the implications on global land use (Haas et al., 2020) or the increasing competition of feed and bioenergy production with human food production (Muscat et al., 2020).

The goal of this thesis is also to provide a group of stakeholders with new and adapted indicators for regional nutrient management. These stakeholders include larger organisations such as the Ellen MacArthur Foundation (EMF), which wants to promote circular economy (CE) practices; smaller start-up companies that want to promote the circularity of nutrients by treating faeces and urine with compost toilets; and environmental government institutions that need indicators to evaluate the state of circularity in their regions. All of these stakeholders need effective indicators that reflect the objectives of the circular nutrient economy.

1.2 Research Objectives

Appropriate circularity indicators are needed to understand nutrient flows on a large scale, i.e. macro scale (Kirchherr et al., 2017) and their impact on sustainability (Harder et al., 2021). A standardised set of indicators is also important for decision-making processes because through them, complex systems may be summarised and reduced into manageable information (Saidani et al., 2019) for the use of various actors in many scientific sectors, including business and policymaking.

Acknowledging the fact that there is a need to develop a set of standardised CIs in the context of regional and interregional nutrient economies, together with the will of enriching with arguments the ongoing debate about what criteria and what outcomes these indicators should assess, are fundamental topics that will be addressed in the present study.

The aim of this paper is to evaluate the current state of development of indicators for assessing circularity in nutrient cycles, and to contribute to the further development of circularity indicators for MFAs of nutrients in regional and interregional systems. Hence, the research question examined in this thesis is: ***What do existing circularity indicators assess on a regional level, considering that CNE definitions are not yet clearly defined? How could these indicators be improved in the context of regional nutrient management?*** This can be broken down into the following two objectives:

1. Suggest improvements to existing circularity indicators for nutrients in material flow analysis on a regional level.
2. Regional system application of the developed set of indicators (1). Case studies evaluation of the circular nutrient economy.

1.3 Delimitations

The focus of this work is centred on nutrient circularity in terms of natural capital, environment limits, energy and biomass production and consumption patterns.

Therefore, economic factors and social variables, are outside of the scope of this thesis. This decision is consistent with the idea of Preisner et al. (2022) that numerical indicators of resource and energy recovery from waste streams have the effect of increasing awareness to adopt CE strategies in economic and social terms.

Although circular nutrient economy operates on all levels of circular economy (micro, meso and macro), this thesis will focus on regional analysis. In the context of CE, the regional level is defined by Kirchherr et al., (2017) as macro level. Therefore, this thesis will not include analysis of the micro level, such as products or companies, nor meso level (e.g. eco-industrial parks).

1.3.1 Focus on Phosphorus

The main reason for the focus on P is due to the difficulty of applying CE principles to biomass. In fact, biomass is not a perdurable material but a substance that changes shape and composition through the production and consumption processes (Navare et al., 2021). P, together with C, N, and K, is a fundamental component of biomass and organic materials. The advantage of P is that it can perform as a very good trace element due to its non-volatile nature and its high binding property into biomass and soil particles (Tanzer & Rechberger, 2020; Papangelou et al., 2021).

Another basic objective of CE is to decouple from the input of virgin materials (non-renewable sources). This concept can easily be applied to P, as it is a critical source, mainly derived from mined phosphate rock (Senthilkumar, et al., 2014), and at the same time it can be a serious pollutant for aquatic environments (Nesme and Withers, 2016).

2. Theoretical framework

This chapter aims to describe the theoretical discourse and previous research on the concepts related to circular nutrient economy as well as clarify which definitions will be used in the present study.

2.1 Background information

Circular economy (CE) aims to replace the linear extract-produce-use-dump model of materials and energy flows, with a circular model where materials should first be reused, and if not possible, remanufactured or recycled into new components, alternatively incinerated for energy recovery or, as a last option, landfilled (Korhonen et al., 2018). So far, CE concepts have been emphasised by businesses and policymakers, while scientific research on the topic is not fully explored, especially from the perspective of sustainable development and planetary boundaries (Korhonen et al., 2018).

There are many definitions of CE, many of them varying substantially in terms of objectives (Geissdoerfer et al., 2017; EMF, 2015; Korhonen et al., 2018; Kirchherr et al., 2017). The lack of consensus can arguably pose problems for measuring and comparison between systems when studies are using different versions of CE.

The core principles of CE, according to Kirchherr et al. (2017) are structured around the following four concepts: the 4R framework (reduce, reuse, recycle, recover), the waste hierarchy (order of ranking of the 4R-framework), the system perspective (micro, meso, macro), and sustainable development. Kirchherr et al. (2017) reviewed 114 available definitions of CE and deduced the following compact verbal definition:

> "A circular economy describes an economic system that is based on business models which replace the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes, thus operating at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, which implies creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations." (Kirchherr, et al., 2017).

Although this definition might be the most widely used, concepts of "restoration by design" (EMF, 2015) and "respecting the natural rate of reproduction" (Korhonen et al., 2018), or "regenerative system" (Geissdoerfer et al., 2017) are less emphasized by Krichherr et al. (2017), who limited the definition regarding the biological context to "creating environmental quality".

The definition of the Ellen MacArthur Foundation (EMF) distinguishes two types of material cycles: technical and biological cycles. In technical cycles, the goal is to maintain, reuse, refurbish and recycle materials. In biological cycles, on the other hand, biogenic materials such as food, feed, and wood, must remain non-toxic and must be reintroduced into the agroecological system at a rate that is in balance with natural processes (EMF; Granta, 2015).

Presumably, according to Kirchherr et al. (2017), the term "environmental quality" includes the regenerative aspect too, but the fact that it is not explicitly mentioned may lead to misinterpretation of how environmental quality should be addressed.

2.1.1 Circular nutrient economy

The concept of circular nutrient economy (CNE) encompasses all types of nutrient management practices aimed at reducing nutrient losses in production systems and increasing nutrient reuse of waste streams back in agricultural production, while providing multiple economic, environmental, and societal benefits (Zhou et al., 2023). In addition to efficiency, the CNE aims for a general reduction of total inputs (Papangelou & E. Mathijs, 2021).

Core elements of the circular bioeconomy are the limited availability of biomass as the prime resource and the sustainability of its management, with the aim of achieving a "functional substitution" of the linear fossil-based economy, i.e. providing the same functions but in a more sustainable way (Befort, 2020).

Similarly, according to Navare et al.'s (2021) definition, biological cycles in the context of CE should consider the 1) sustainability of sourcing materials, 2) the cascading use of materials across consumption compartments, 3) measuring the efficiency of nutrient re-entry into biological cycles, and 4) assessing the environmental impact of using biogenic resources (Navare et al., 2021).

2.1.2 Bioregions

A circular nutrient economy analysis should not treat all regions equally because some have more diverse and fertile land for crop production than others. In the 1970's bioregions were defined as biologically significant areas around the globe with individual characteristics of biodiversity and fertile soil formation resulting from natural landscape development, plants and animals, and their domestication by humans (Newkirk A. V., 1975). The concept of "identity" of biocultural systems, with specific occurring natural resources, climatic conditions, morphology, and deriving interactive watersheds, was elaborated to recognize the risks of exploiting single regions with unique resources for the benefit of other regions (Berry Thomas, 1984).

For a regional systematic evaluation of the macro system concept, FAO developed the Agro-Ecological Zones (AEZ) methodology, which provides a framework for quantifying multiple spatial characteristics of regions to measure land productivity using, for instance, climate, soil moisture regimes, and share of protected areas (Fischer et al., 2021).

In this context, it follows that when comparing two macro regions in terms of their level of nutrient circularity, the regional and current biophysical and cultural differences can be considered to get a more holistic understanding of the system boundary and its self-sufficiency potential versus its import dependency.

2.1.3 The meaning of production in agricultural terms

In CE, the production of goods in the technosphere can be broken down to a factory plant with specific required inputs (technology, energy, and raw materials) and a specific function (product oriented). From a technical point of view, the production of materials can take place anywhere.

In agricultural production, which is linked to the ecosphere, soils are the basis to produce biomass, which, unlike in the technosphere, is bioregion-dependent and varies in efficiency depending on the availability of land, soil fertility, climate, solar radiation, and the water cycle. On top of this, soils provide ecosystem functions beyond food production (product and environment oriented).

This means that, in addition to social, economic and political factors, production in biological systems is governed by site-specific conditions and must take into account its multi-functionality.

This fundamental difference between the technosphere and the ecosphere was neglected during the Green Revolution in Europe, and it is also not very much considered in CNE regional assessments so far. As a result, agricultural soils were viewed as industrial production sites (food oriented) and technological improvements make it possible to increase yields (Notarnicola et al., 2017).

The technical interpretation of agricultural production is still conceptualized in current system analysis methodologies. In fact, many food-related Life Cycle Assessments (LCA) studies today still do not include impacts on soil fertility, water balance, and biodiversity, which means that they do not address natural capital conservation and long-term food security (Notarnicola et al., 2017).

2.1.4 Material Flow Analysis and Circularity Indicators

Material Flow Analysis (MFA) is a multipurpose family of tools based on the mass balance principle. MFA is used to identify the input, throughput, and output of physical flows of any material in a defined system. MFA can be applied to either economic, natural resource management or environmental policy (OECD, 2008).

MFA can be applied at different levels: from a natural unit, such as a soil ecosystem or an industrial plant, to a territorial or global scale to analyse material exchanges between countries (plastics, wood, metallic materials, etc.).

In the context of industrial symbiosis, a precursor concept of CE, initial indicators have been developed to measure the socioeconomic metabolism at the national level, such as the domestic material input (DMI), domestic material consumption (DMC), or the total material requirement (TMR) (Graedel and Lifset, 2016).

There is a consensus in the literature to differentiate CE indicators into two classes: there are inherent CIs, which measure the performance of material recirculation rates, and consequential CIs, which is a group of indicators that measure the consequences of CE loops on the environment, society, and economy (Saidani et al. (2019); Vural Gursel et al. (2023)).

China was one of the first countries to develop national CE indicators, one set for the macro level and one for the meso level (Geng et al., 2012). Based on the 4R principles and the MFA model, the four categories that are contained are resource output (GDP production), resource consumption, resource integrated use (level of material circularity), and waste disposal/pollution emissions (Geng et al., 2012).

CE principles such as "reuse" may have different interpretations, depending on the level of system analysis. In WWTPs at the micro level, an example is a developed CE indicator for reuse of sewage sludge, which was used in a study that defined the proportion of sewage sludge that was used in anaerobic digestion (AD) as a reused fraction, even though the digested sludge was ultimately either landfilled or incinerated (Kiselev et al., 2019). In contrast to this interpretation, at the macro level, the "reuse" principle of AD sludge clearly refers to land application on farms.

2.2 Key concepts for indicator development

2.2.1 Hierarchical concepts in CNE

The Waste Hierarchy (WH) concept has been adapted for decades to show which strategies are more sustainable than others, mainly between landfilling, recycling, reuse, and prevention of waste generation (Schmidt Rivera, et al., 2020).

However, due to the complexity of the waste material composition, and the missing inclusion of economic factors, so far, the WH has been considered as unsatisfactory for application in the field of CE (Van Ewijk & Stegemann, 2016).

Muscat et al. (2021) defined principles specifically for circular bioeconomy. In their concepts the idea is to prioritize patterns of biomass production and consumption (Figure 1). This aspect should be seriously addressed, considering that biofuels and high-protein feeds for livestock in the global North are at the expense of global food security and malnutrition in the global South.

After consumption, the best option for reuse is clearly determined by the level of contamination. A waste hierarchy-based management framework in the context of nutrient systems was developed by McConville et al. (2015), which applies five waste management options: reduce, reuse, recycle, incinerate, and dispose. In this conceptualization *reduce* refers to the generation of organic waste and its contamination, and *reuse* refers to practices that reuse organic waste as it is, when possible. When materials are not safe for direct reuse, *recycling* allows the creation of new products (compost, biogas production). Beside volume reduction of waste and energy recovery, *incineration* is considered a less attractive option due to high C & N losses and reduced P availability in the ash. Finally, *disposal* is the less favourable option, if the other options cannot be implemented (McConville et al., 2015). These principles are in line with the prioritization approach of Papargyropoulou et al (2014) presented in following Figure 2 and the CE concepts discussed earlier in the introduction, which will be further explained in the following chapters.

2.2.2 Application of hierarchical concepts at the input stage

The argument of Muscat et al. (2020) is to achieve an effective use of biomass, rather than focusing on efficiency (narrowing, slowing) alone. This follows the principle of the "hierarchy of considerations", which involves prioritizing the use of biomass with respect to the surrounding biophysical limits and human needs (Fischer et al., 2007).

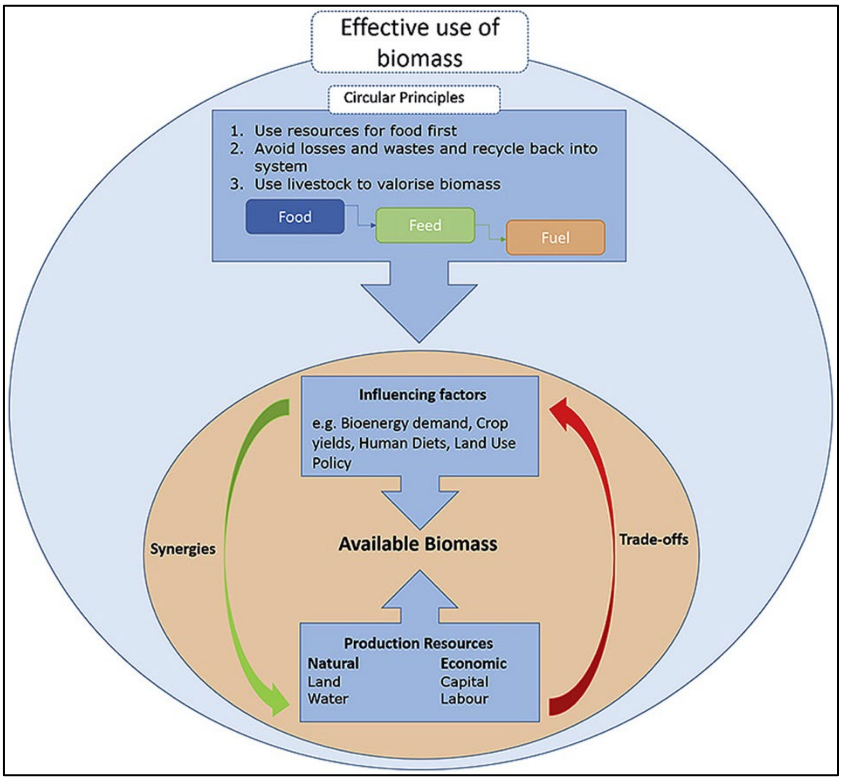

Figure 1. Framework for circular biomass use that prioritizes food production over feed production and at last bioenergy production (Source: original illustration from Muscat et al. (2020))

The highest priority for biomass consumption should be for food for humans, as food security is the highest priority (Muscat et al., 2020). This principle also applies to related resources such as land, water, capital, and labour. Similarly, by-products and food waste should be used first as food, if possible, and only if inedible for humans as feed, and finally as a bioenergy source (Muscat et al., 2020).

In the European context livestock consumption plays a key role in circularity (Koppelmäki et al., 2021). Nevertheless, land use efficiency of livestock production is an ongoing open debate, which has different outcomes depending on the metrics used to evaluate its impacts for future food security and the environment.

In fact, by modelling environmental impacts, reducing meat consumption by only 50% would result in a 40% reduction in N pollution, a 25-40% reduction of GHGs, and an increase in cropland availability for more crop production (Westhoek et al., 2014). However, some authors argue that marginal land used for crop production and not grazing animals, will be less efficient in sourcing human edible protein (Van Zanten et al., 2016). Particularly on marginal land that is too steep or not fertile enough to sustain crop production, ruminants have great potential to utilize low-opportunity-cost biomass that is not suitable for direct human consumption (grass, crop residues, by-products from the food industry, or post-consumption losses and waste), generating also local organic fertilizer (manure), promote grassland conservation without the use of machinery, and deliver high-value food products (Muscat et al., 2020).

In Austria, Germany, and Denmark, crops such as silage maize are becoming an attractive feedstock source for biogas production due to their high methane yields, nevertheless restrictions due to feed-food competition are expected to limit this trend in the future, prioritizing the use of crop residues and organic waste streams for bioenergy (Scarlat et al., 2018). Some studies recognize the potential of *Miscanthus* as an alternative crop for direct biogas production, which seems to be a suitable alternative on less productive marginal soils, ensuring better C sequestration and not interfering with food production (Tavakoli-Hashjini et al., 2020). However, in the literature there seems to be no agreement on what the best use of marginal land would be, if it were to be used for livestock grazing, biofuels, or even rewilding purposes (Muscat et al., 2020).

Consuming nutrient rich materials produced outside the EU always has environmental and social impacts elsewhere. Phosphate-containing mineral fertilisers are imported virgin resources extracted through mining activities, causing external/internal environmental impacts, and ultimately contributing to the depletion of a finite resource (Reijnders, 2014).

Imported virgin mineral fertiliser does not meet any of the CNE objectives. On the other hand, imports of sewage sludge, composted biowaste, and chemical recycled sources, are products that address regeneration, reuse, and up-cycling. There are good reasons to argue that importing recovered nutrients in any form to a nutrient depleted region should be prioritized, while importing recovered nutrients to regions with high nutrient stocks in farmland should be less encouraged.

2.2.3 Application of hierarchical concepts at the output stage

Reducing losses and waste generation are essential goals in CNE. At this level, improving resource-use efficiency by coupling cascading biomass use, waste management, and consumption reduction are fundamental actions to be addressed (Muscat et al., 2020).

At the post-consumption stage, it has been proposed to address the prevention and management of food waste to ensure sustainability by approaching the problem with a prioritization approach (Papargyropoulou et al., 2014). Various types of losses occur along the Food Supply Chain (FSC) between harvest, processing, distribution, consumption, and disposal. Ishanguluyyev et al. (2019) coined the term food loss and waste (FLW), which is the sum of food loss (FL) and food waste (FW). FL is defined as the reduction in weight of food products during production, handling & storage, and processing, which can be caused by inefficient supply chain management, safety standards, or environmental factors.

Food waste is defined by Ishangulyyev et al. (2019) as losses occurring during final distribution and consumption stages. An important distinction is between unavoidable and avoidable FLW: the former consists of inedible parts (bones, vegetable peels, etc.), while avoidable food is material that could have been eaten or used at some point in the FSC (Ishangulyyev et al., 2019).

Human excreta in this context are considered as unavoidable FLW, given also the reframing efforts found in literature (Harder et al, 2020).

In their hierarchical approach, Papargyropoulou et al. (2014) introduce the concept of food surplus, which is edible food that should be either reduced or reused, and food waste, which can be avoidable or unavoidable, the former can be prevented or recycled, while the latter can be upcycled as feed first and otherwise downcycled for material and energy recovery (Figure 2).

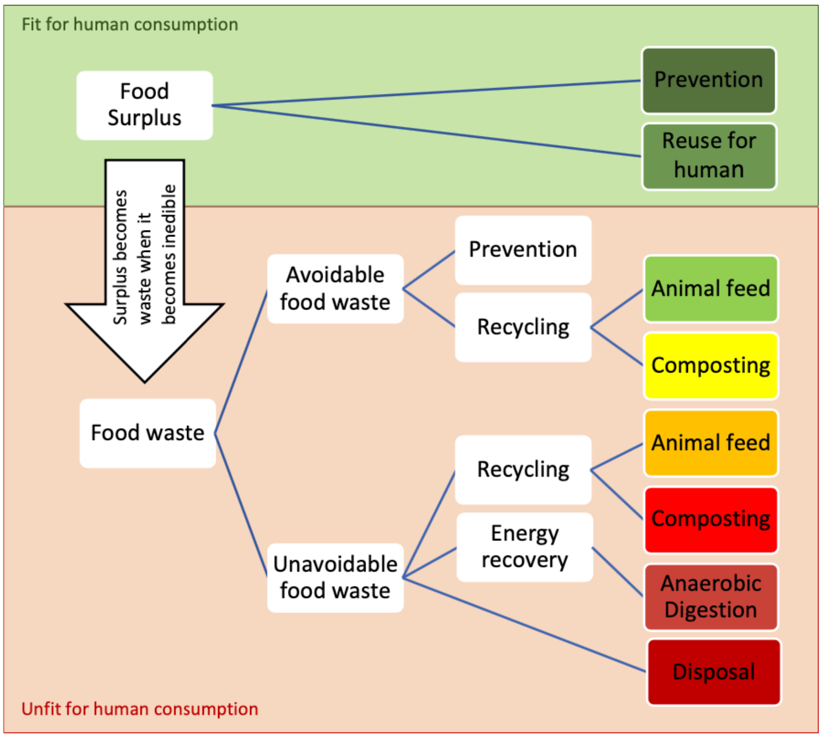

Figure 2. Food surplus and waste framework from Papargyropoulou et al. (2014). Green shades reflect the most favourable option, red the least favourable (adapted illustration by Alan Gerster)

High meat and high calorie diets in high-income countries require larger areas of land and are therefore considered a key factor in the competition between food, livestock feed and biofuel production (Zasada et al., 2019). For this reason, at the European level, two important goals in line with CE principles are to reduce animal-sourced foods and calorie consumption in general (Muscat et al., 2020).

There are also still major policy differences between EU countries on how to regulate sewage reuse. For example, the use of sewage sludge on agricultural land is fully prohibited in Switzerland, while it is legal in Denmark, Sweden and Germany in respect to certain threshold values (Johansson & Krook, 2021). There are studies that argue that there are no serious risks associated with the application of regulated sewage sludge to farmland (Magid, et al., 2020), others argue that, even if parameters are in line with local regulations, there is no guarantee that hazardous substances have been fully eliminated when applying sewage sludge (Linderholm, et al., 2012). Increasing the number of pollutants monitored does not seem to be efficient either; the use of 10-15 selected substances as contamination indicators is common practice in Europe, with Sweden introducing the REVAQ certification, which monitors up to 60 substances. However, despite more analysis investments, Swedish farmers remained sceptical about the unaddressed “cocktail effects” of sludge reuse (Johansson & Krook, 2021). Moreover, sewage sludge itself is not consistent with a critical CE goal of "*ensuring that biological materials remain uncontaminated and biologically accessible*" (Goddin et al., 2019), which emphasises the need to avoid contamination via mixing of materials rather than promoting contaminant removal technologies.

The use of organic waste that originates from a separate collection system is allowed in organic farming in Germany according to the Regulation EU 2021/1165 and if the heavy metal and external materials limits according to the guidelines of Bioland and Naturland are compiled (Gottschall et al., 2023). Nevertheless, as for sewage reuse, the risks associated with unseen contaminants still exist and unpredictable "cocktail effects" are a serious concern if composting practices are to be upscaled and established in the long term (Isenhour et al., 2022).

The production of struvite from sludge of WWTP, being of mineral nature, does not add organic matter to the fields, but it does recover nutrients from a waste stream, addressing reuse, value-added products, and safety goals. However, missing soil conditioning benefits of struvite recycling can be argued to have a negative contribution to CNE practices, even though it is characterised as a safe fertiliser (Nagy, et al., 2019), making it difficult to classify struvite benefits from a hierarchical perspective. In this study it is suggests that closing nutrient cycles on agricultural land by regenerating with the addition of C-rich substrates should be prioritised over recycling pathways by reused chemical fertilisation alone.

Unavoidable food waste, if not fed to animals or composted, can be digested to recover energy. These materials should be from sustainable production, uncontaminated, and become beneficial to the ecosystem in which they are reintroduced (Goddin et al., 2019). If all other options are not possible due to contamination, incineration remains as last energy recovery strategy which is in accordance with CNE principles.

2.2.4 Nutrient recovery technologies

Technological solutions for processing organic waste or by-products into new fertiliser products are gradually becoming more widespread (Valve et al., 2020). In some cases, the technologies can be cascaded, but they can also be operated individually. As reported by Valve et al. (2020) the four major categories for nutrient recovery technologies are physical, biological, thermal, and chemical (Table 1).

Beside biogas production, AD presents supplementary advantages compared to the other technologies. In fact, the output material (digestate) contains a higher share of NH_4^+ (Valve et al., 2020) than the input waste material. Ammonium is therefore more available to plants and less likely to leach into groundwater. In addition, digestate can be further separated and concentrated into liquid and solid fractions, which would allow the application of additional technologies such as ammonia stripping, or membrane technology, contributing to the production of various types of fertiliser products, while in the end also producing solid biomass rich in P for land application (Valve et al., 2020).

The main advantages of nutrient recovery are organic waste volume reduction, by separating into liquid and solid fractions, and the elimination of hygienic risks (Valve et al., 2020). Especially in biological treatments (Table 1), recycled nutrients bring the greatest potential as soil conditioning (Valve et al., 2020). All technologies require appropriate processing infrastructure, storage, and application methods. This is especially due to N and its volatile nature. For this reason, closed systems are recommended to prevent major N-losses (Valve et al., 2020).

There is an increasing interest in chemical nutrient recovery as well, such as P-recovery from ash from incineration plants or struvite removal from wastewater, particularly because it is more efficient in overcoming barriers posed by the risk of pathogens from animal carcasses or sewage sludge. However, this approach has been criticized for compromising the return of organic matter that serves as a C sink in agriculture, which could affect soil quality and resilience in the long term (Yuille et al., 2022).

Table 1. Processing technologies for nutrient recovery (modified from Valve et al. (2020))

Category	Technology	Purpose	N-fate	P-fate	*Soil benefit
Physical	*Mechanical separation*	Solid / liquid separation	Liquid fraction	Solid fraction	0
	Thermal drying and concentration		Risk of N-volatilisation (open system)	Solid fraction	0
	Membrane technologies		Chemical separation		–
Biological	*Composting*	Biomass stabilisation & sanitation	Risk of N-volatilisation (open system)	Composted biomass	+
	Anaerobic digestion (AD)	Biomass stabilisation, sanitation & energy production	Increase of share of N-soluble	Retained in biomass	+
Thermal	*Pyrolysis, Thermal gasification, incineration*	Reduction of water content, energy production	N-capture required before drying biomass	High temperature reduces P-available for crops	0
Chemical	*Ammonia stripping, struvite crystallisation*	Reconditioning the biomass for further processing	Inorganic N product	Inorganic P product	–

*the output materials can have a soil conditioning contribution and for each technology this aspect has been represented as positive (+), negative (-) or neutral/unknown (0)

2.2.5 Upstream contamination of organic waste

If organic waste is to be valorised and recirculated, it must be done without contaminating the receiving ecosystems. In developed countries waste recyclers working in biogas or composting plants are responsible for the technical processes and the quality of the final product, but these facilities have limited resources to control bioaccumulation of contaminants along the food chain. Composting and digestion plants are typically more preoccupied with visible impurities such as plastics, glass, and any kind of physical scraps, while only a minority of these facilities is concerned with the invisible contaminants such as preservatives, herbicide residues, per- and polyfluoroalkyl substances (PFAS), microplastic, and antibiotic resistance genes (ARGs), which can accumulate on farmland if used as soil amendments (Isenhour et al., 2022).

The responsibility for providing safe organic fertilisers shifts along the farm and the food processing systems down to the consumer stage, where producers and consumers have the power to make important decisions about the materials and chemicals used which will accumulate further downstream (Isenhour et al., 2022). Domestic wastewater from densely populated urban areas is also usually mixed with industrial wastewater, stormwater (microplastics from roads), and greywater (detergents, heavy metals) resulting in high levels of various contaminants in the sludge. One way to better recover nutrients from wastewater flows, for example, is to have source separated systems of human excreta which have less contamination originated from greywater streams (McConville et al., 2015) and would therefore offer more safer reuse and recycle of organic residues.

2.2.6 Regeneration and restoration in CNE

Regarding regeneration and restoration there is currently no agreement on how to define it in the context of CNE (Morseletto, 2020).

Restoration, according to Morseletto et al. (2020), refers to an economy that should use natural capital by promoting the return of resources to a previous or original state. What is meant by pristine is unclear. One could restore agricultural land as it was before the introduction of industrial mineral fertilizers, when only organic nutrient sources were applied (Koppelmäki et al., 2021) or by rewilding parts of agricultural land, although negatively affecting regional food production.

On the other side, regeneration has been defined as a category of practices that promote fertility of agricultural land, recover productive sites form disturbances and rebuild over-exploited ecological and agricultural functions (Morseletto, 2020).

Biologically treated organic waste (AD sludge, compost), in contrast to inorganic fertilisers, have the potential benefit of producing a soil conditioner for humus formation that can be applied on agricultural land (Hermann, et al., 2011). Which is, together with atmospheric C sequestration, an important goal in biological systems according to CNE definition in biological systems.

One last aspect is the safety and compatibility of materials. Morseletto et al. (2020) support the idea that in the ecosphere the reintroduction of biological materials from CE into complex ecosystems should follow strict protocols that ensure compatibility and toxicity. The authors suggest the idea that the guidelines and standards of restoration ecology should be aligned with the goals of CE, both concepts still in their infancy.

2.2.7 Biomass use

Since biomass is a limited renewable resource and the shift away from fossil fuels will boost biofuels consumption, agricultural soils and biodiversity conservation are likely to come under pressure (Haas et al., 2020).

Given the growing demand for biofuels, especially in Germany which has the highest number of biogas plants in Europe (Scarlat et al., 2018), it is likely that biomass will increase in value. Because of this, even greater attention should be paid to safeguarding primary resources in accordance with natural cycles (Muscat et al., 2021; Zabaniotou et al., 2018). This includes protecting biodiversity by setting a global zero-deforestation target and restore degraded soils by applying biodiversity-enhancing practices such as crop rotation, agroforestry, or organic farming (Muscat et al., 2021).

2.3 Literature summary on circularity indicators

In the literature six articles were found that specifically applied self-developed circularity indicators, which are presented in Table 2.

The most common indicator is Circularity (C), which was used in many ways in the selected studies (Tabel 2). In their scenarios Tanzer et al. (2020) evaluated the impact of reducing system demand, increasing recovery, and reducing emissions. Tanzer et al. (2020) adapted the circularity indicator, which they conclude is well suited to measure the increase or decrease of recycling activities for the entire Austrian nutrient system.

Cobo et al. (2018) developed a circularity indicator that is based on the amount of material (i) entering a given recycling process (j), the amount of (i) lost during this recycling process and the final amount of (i) present in a new production process (k) (Table 1). In this conceptualisation of Cobo et al. (2018), the recycling aspect (j) and the recirculation aspect (i) are integrated in one formula. This conceptualization is the most common, that is like the MCI (Material Circularity Indicator) developed by the EMF for the micro level (EMF, 2015).

Other studies decided to assess circularity in three areas: city self-sufficiency, food system perspective and open-loop recycling (Papangelou et al., 2020). The authors used the City Circularity (CC), Food Circularity (FC) and Weak Circularity (WC) (Table 2), which is an attempt to expand the analysis depending on the level of the system boundary.

Some authors decided to separate the rural from the urban areas: Harder, et al. (2021) used the Input Circularity (IC) to measure the proportion of crop removal that can be achieved by nutrient cycling on the farm. Similarly, Papangelou et al. (2021) use the so-called Secondary to total input (%), which is used to calculate the amount of recovered material to the productive subsystems of agriculture and food production. These two Input Circulatory indicators are not applicable at the waste management subsystem at the output stage.

Concerning the system output, the recycling concept is largely addressed in the indicators of Table 2, which shows that nutrient circularity assessments have focused intensively on the recycling efficiency of the total organic urban waste (Koppelmäki, et al., 2021).

Harder et al. (2021) used the “recovery efficiency in organic residuals”, considering all possible recovery options by using the Output Circularity (OC), which measures the proportion of nutrients that are recycled from the waste management facilities. Papangelou et al. (2021) did similar by applying the recycling rate (RR), as it was also the case for Food, City and Weak Circularity of Papangelou et al. (2020), and more generally it also works with the approach of Tanzer et al. (2020) with the Circularity indicator.

Table 2. Circularity indicators of six specific study cases evaluating macro nutrient circularity.

Indicator	Definition	Unit	Source
City Circularity	$\frac{P\ reused\ within\ the\ city}{Total\ P\ input}$	%	(Papangelou, et al., 2020)
Food Circularity	$\frac{P\ reused\ or\ reusable\ in\ agriculture}{Total\ P\ input}$	%	
Weak Circularity	$\frac{P\ reused}{Total\ P\ input}$	%	
Circularity (C)	*Recirculated waste (EOL+BP) * 100 / Throughput (ST)*	0-100 (0 = linear, 100 = circular)	(Tanzer & Rechberger, 2020)
SCE	$SCE = \frac{H_1 - H_4}{H_1} * 100$	0-100 (0 = no changes in entropy, 100 = pure mass flow)	
System openness	*Nu in org. residuals / Nu removed by crops (internal or external SB)*	<1 (nutrient depletion) >1 (nutrient accumulation)	(Harder, et al., 2021)
Nu self-reliance (Input circularity)	*Recirculation to the food system, or crop removal (internal or external SB)*		
Recycling rate (Output circularity)	*Recirculation from the WM (internal or external SB)*		
Biomass production for food	*Protein production (kg ha^{-1}) in relation to consumption (kg), connection to national and global scales*	%, Gg flows	(Koppelmäki, et al., 2021)
Biomass production for feed	*Feed self-sufficiency (FSS), regional feed surplus*	%, kg ha^{-1}	
Biomass production for energy	*Biogas production potential compared to energy consumption of farms and mineral N manufacturing*	MWh ha^{-1}	
N cycling	*Agricultural field balances, shared of recycled N*	N kg ha^{-1}, %	
Total Input	*Sum of all inputs into the subsystem*	Kg P/cap*a	(Papangelou & Mathijs, 2021)
P Use Efficiency	*Products / Total input*	%	
Secondary to total Input	*Secondary input / Total input*	%	
Recycling Rate	*Reused flows / Total waste generated*	%	
Losses	*Emissions & Losses / Total input*	%	
CI_i	$CI_i = \frac{\sum_{k=1}^{m}\sum_{j=1}^{n} R_{ijk}\eta_{r_{ij}}\eta_{p_{ik}}}{W_i}$ [a] (1 = total i is entered in a new consumption process, 0 = total i not recovered (incineration/landfill))	Values (0 – 1)[a]	(Cobo, et al., 2018)
LCA	*CI_i integrated with GW, ME, and FE*	{Ci max, LCAmin}	

Abbreviations: WM = waste management, LCA = life cycle assessment, EOL = end of life material, BP = by-products of production processes, ST = sum of: extracted raw materials + environmental deposition/extraction + consumption deposition + net import (raw material + goods) + waste, SCE = Substance Concentration Efficiency, H = statistical entropy in the first (1) and final (4) stage (input, production, consumption, waste management) (Rechberger & Brunner, 2002), CI_i = Circularity indicator of component i, W_i= amount of i in waste (kg), R_{ijk}= amount of i that enters recycling process j, $\eta_{r_{ij}}$= recycling efficiency of process j, $\eta_{p_{ik}}$= efficiency of production process k of incorporating i in a new consumption subsystem, GW = global warming, ME = marine eutrophication, FE = fresh water eutrophication.

Harder et al. (2021) used the indicator System Openness, as "*the degree to which nutrients removed from agricultural land in one place make their way into organic residuals in another place*" to expand the analysis of nutrient circularity by including imports and exports of commodities and fertilisers into and out of a defined geographic area to the main nutrients hotspot subsystems: production, consumption, and waste management (Harder et al., 2021). According to Van der Wiel et al. (2019), these subsystems are crucial when assessing circularity. They broke this down further into the following categories: crop production, livestock production, food and feed processing, consumption, and waste management.

To track the sites of production and consumption relative to the system boundary (SB), Harder's et al. (2021) framework breaks down the nutrient flows into 9 pathways of unique combinations, which can be either outside (EXT) or inside (INT) the SB. One path, for example, is agricultural land, livestock production and final food consumption that occur entirely within the system boundary, which would be the most localised pathway option (INT - INT - INT). Another more globalized path-example is external feed imports to feed local livestock combined with export of the animal products for consumption in another region (EXT - INT - EXT).

Koppelmäki et al. (2021) used the N cycling indicator to measure the field balances, or similarly Papangelou & Mathijs (2021) used the Losses indicator to assess process efficiencies. A newer approach was designed by Tanzer et al. (2020), which applied the substance concentration efficiency (SCE) indicator, which measures the degree of dilution or concentration of a substance. Dilution typically refers to emissions or mixing of materials, and concentration refers to collection or recycling. They conclude that SCE is well suited for assessing emissions, the reduction of material inputs, and changes in process efficiencies.

At the production side, Harder et al. (2021) used "the nutrient use efficiency in primary production" (net crop removal and fertiliser requirements) as an indicator for biomass production. Of particular interest is the distinction of biomass use into food, feed, and energy by Koppelmäki, et al. (2021), which also integrates the EMF principle that energy recovery is considered as the lowest form of circularity (Goddin et al., 2019), but plays an important role in the future contribution of fossil-free energy sources.

2.4 Addressed conceptual gaps for CIs development

To efficiently assess the nutrient circularity of a region, a set of specific indicators is needed (Moraga et al., 2019). First, in the context of agri-food-waste systems, CIs should measure the progress towards CNE goals and present the extension of the linear flows in contrast to the circular flows (Moraga et al., 2019). Second, the circularity indicators for the macro system should consider the type of agriculture, whether intensive or extensive, and the context, whether urban or rural (Aznar-Sánchez et al. (2020). Third, sustainability indicators must be additionally integrated to measure the impact of CE on the SDGs (Aznar-Sánchez et al. (2020).To understand nutrient flows on a large scale it has been suggested that an appropriate way is to conceptualise the flows interaction between the ecological and societal components to understand the internal, and external material flows and ways to improve their impact on sustainability (Harder et al., 2021).

2.4.1 Recycling

As Table 2 shows, CIs in agro-food-waste systems are currently well established to address aspects of “closing” (Recycling Rate, Circularity) and “narrowing” (Efficiency, minimize losses).

Recycling is an important principle within CE. But circularity of nutrients is not achieved by recycling alone (Pires & Martinho, 2019). Especially for the waste management sector, for example, recycling rate (RR) does not address nuances of upcycling and downcycling measures (e.g., value-added products, cascading of biological materials), and recycling is often limited to information about recycled material without further details concerning the final use of recycled materials. These limitations have been therefore criticized of not being holistic enough (Pires & Martinho, 2019).

As is the case for the flow “recycled waste” used in the CI of study of Tanzer & Rechberger (2020) (Table 2), a clear qualitative distinction between the fate of its flows is not given, even though knowing if the materials have been upcycled or downcycled is key for CNE goals.

2.4.2 Subsystem circularity rather than system circularity

Tanzer et al. (2020) adopted Circularity although a distinction of production processes has not been done, merging livestock production with crop production. Processing of feed and food subsystems was also not included. In their method, the circularity indicator only accounts for recycled materials over all the system (system throughput), without differentiating between urban waste management and organic waste generated at the farm level.

The distinction of three circularity indicators of Papangelou et al. (2020) (Table 2) shows that the location and agricultural processes where nutrients are reintegrated into the system is influencing the overall circularity. Theoretically, higher circularity would be expected if production processes of urban food would be intensified, especially soil less practices such as urban gardening, vertical gardening, backyard chickens, or aquaculture.

2.4.3 Scarcity in biological systems

Another missing aspect is the regional biophysical constraints determined by soil fertility, climate, and water availability that limits biomass production. According to the EMF, there is no metric to define the scarcity of biological materials (Goddin et al., 2019). As also Liobikiene et al. (2019) proposes, three criteria to be measured at the environmental dimension which are: I) overall contribution of bioeconomy to the reduction of environmental impact, II) at the supply side the “biocapacity”: the consumption and potential availability of biomass, and last III) at the demand side: the “land footprint” of bioresources consumption.

No clear definition of “sustained production” of biological materials was found in the circular economy concepts either, although various indicators can be used for this scope depending on the material being produced; no agreement has been found on which indicators work best (Goddin et al., 2019).

2.4.4 The context specific role of livestock production

Koppelmäki et al. (2021) argue that circular food production should be based on local resources and that "the capacity of producing feed determines the scale and intensity of livestock production". The cases listed in Table 2 do not consider the impact of the scale of livestock production and the regional capacity to uphold livestock production. The assessment of the balance between animal sourced food production and land capacity to sustain it is clearly lacking in the summary. Its importance is well explored by a study which found that coupled systems were found to be nutrient efficient when straw waste was used as animal feed and a specific number of livestock density (15 pigs ha^{-1}) met the nitrogen demand of 75 kg N ha^{-1} required by a specific livestock associated crop cultivation (Jin et al., 2020). In this example fewer pigs meant the need to apply other sources of nutrients such as synthetic fertilizers, but more pigs meant environmental losses or manure transportation to neighbouring farms if not landfilled. At the regional level, Jin et al. (2020) concludes that relocating livestock according to cropland production would reduce transportation costs and promote nutrient circularity.

If the agroecological constraints are not respected and reallocation of livestock is not chosen as a strategy, Papangelou et al. (2020) point out that excess manure production of regions with intense livestock must either be exported or incinerated. In such a scenario, their suggestion is to identify possible sites for the reuse of manure out or in proximity of the system boundary.

When considering manure use it is also required to better understand its flows within the system boundary since often mass flows are estimated based on livestock units, but in literature so far it is rarely specified how much is safely collected in stables and how much is unavailable, that is left on the grassland.

2.4.5 Toxicity and regeneration assessment

The EMF states that recycled materials must be non-toxic according to recognized standards and compatible to the environment of application (Goddin et al., 2019). However, toxicity assessment did not play a central role in any of the studies listed in Table 2. For example, Tanzer et al. (2020) did not measure effects on regeneration, or safety of materials.. Cobo et al. (2018) assessed the global warming and eutrophication potential which measure impact to the environment, but do not focus on material safeness for human health.

Poponi et al. (2022) identified the human Toxicity Potential Indicator to be used in the context of agri-food-waste to assess contamination, but no practical example of how to apply toxicity to the whole system was found in the review (Table 2) and this was identified as a major gap in the literature across all the stages of production and consumption processes.

Regarding regeneration, a clear objective of the CE principles, it has not been considered in the studies of Table 2. This might be explained by the fact that regeneration is a qualitative aspect that, by definition, does not fit into the performance-based indicators of Table 2 (e.g., circularity, recycling rate).

3. Methods

This section describes the methodological approaches used to address research objectives: i) further development of circularity indicators for regional nutrient MFA, and ii) regional system application of the developed set of indicators. From what has been learned from the conceptual gaps found in literature, in this study it has been recognized that macro-level CIs are predominantly either performance-based indicators and less focused on CNE objectives.

Circularity is not easy to measure at the system level and it is advised to focus on each subsystem (Van Der Wiel et al., 2021). Both the recycling and recirculation fractions should be also measured by different indicators; the secondary use in agriculture, or *Input Circularity*, and for recirculation from waste sources the *Output Circularity*, following Harder et al.'s (2021) definition.

In this thesis it was decided to focus on the *Output Circularity*, focusing solely on the system outflows. The theoretical framework of chapter 2 allows to deduce following criteria that are going to be addressed for developing circularity indicators at the regional level:

Criterium 1

Recycling or reusing are concepts that according to the CNE definition, need a clear ranking system that must be respected (4R framework), which promotes some strategies over others (reduce over reuse, reuse over recycle, etc.). Indicators from the literature summary are failing in addressing these important differences, for example by not differentiating between value added products or prioritization of food production over energy production.

Criterium 2

Clarifying the agricultural/regional context (intensive/extensive), the soil potential and biomass production limits of the region, the level of livestock-crop connectivity, and the global interdependence of the region (system openness), all these aspects determine the regional specific CNE goals to be addressed.

Criterium 3

Indicators should also be able to address toxicity and regeneration at all system stages. This will provide a qualitative measure of whether processes are safe and regenerative from the farm to the consumer and back.

3.1 Developed analytical framework

3.1.1 Hierarchy analysis framework for regional CNE

To support the circularity indicators development approach of this study, crucial requirements of CNE found previously in literature are considered and listed in Table 3. The CNE requirements are then translated to apply to P flows, given that in this project it was decided to use P as the reference nutrient to explore the goals of CE in biological cycles. Table 3 addresses the 4R framework, which is related to *criterium 1*. The objectives (OB) listed in Table 3 present a short description, which is a summary of the objectives derived from the theoretical concepts of CNE from various sources.

Table 3. Objectives of CNE in agro-food-waste nutrient cycles. (OB = objective). An interpretation was given from the P-perspective.

OB	Description	Sources	Strategy	Applied on P
1	**Virgin Input:** Reduce input of virgin resources	1; 4	Reducing	*Reduce food consumption, reduce use of mineral fertiliser. When possible, use organic or recycled sources*
2	**Losses:** Minimize losses by increasing resource efficiency and reduce waste	1; 2	Narrowing	*Increase efficiency in agricultural processes and waste management, reduce losses to the environment*
3	**Reuse:** Increase reused / recycled materials	1; 2; 3; 5	Closing	*Increase reuse of P by-products (edible food waste, crops for animal consumption)*
4	**Value:** Maximise value, utility, and durability of products, maximise resource output	1; 2; 3; 4; 6	Slowing	*Cascade materials into new P-containing organic products before incineration or landfill (digestate, composting, bio polymers, BSF protein production),*
5	**Regeneration:** Limited by regeneration rate of natural systems and seasonality, preserve the biological function	1; 2; 3; 5	Regeneration	*Maintain ecosystem and agricultural functions, soil conditioning with organic matter, ecological farming to promote biodiversity*
6	**Safety:** At the end-of-life biodegrade and safely return to the natural ecosystems, redesign products and waste	1; 2; 4; 5; 6	Regeneration	*Waste fraction containing P should return safely, non-toxic, and hygienic back to natural and agricultural systems. Address toxicity of P-products from production to consumption stages*
7	**Eutrophication**: Reduce environmental impacts	1; 2; 5	Narrowing	*Reduce P eutrophication in waterbodies (effect of OB 2)*
8	**Energy:** Recover embodied energy (biogas, incineration, landfill gas capturing)	3	Slowing	*If toxicity does not allow reuse, before landfilling, energy recovery of waste fraction containing P should be prioritized*

[1] (Navare, et al., 2021); [2](Velasco-Muñoz, et al., 2021); [3](Moraga, et al., 2019); [4](Kusumo, et al., 2022); [5](Aznar-Sánchez, et al., 2020); [6](Vert et al., 2012)

Table 4 instead shows the strategies for each subsystem that could be implemented to promote CNE (adapted from McConville et al. (2015)). Regarding CNE strategies, green indicates safe and source-separated materials, while red denotes mixed and possibly contaminated materials (Table 4). Some studies (Cordell et al., 2012) merge crop and livestock production into *agriculture*, but due to the impact of livestock on circularity as presented before, it is important to keep these subsystems separate (Table 4). Specific performance indicators for each strategy to measure progress are desirable but may vary by region due to differences in soil type, historical agricultural context (livestock or crop intensive), the industry, urbanization, and population size.

For the development of circularity indicators Van Der Wiel et al.'s (2019) five key subsystems were used: crop production, livestock production, food and feed processing, human consumption, and waste management.

The proposed hierarchy analysis framework (Table 4) allows to track relevant areas in CNE from an intrinsic perspective. This is in accordance with Vural Gursel et al. (2023), which proposed to focus on two distinct categories: intrinsic and impact areas with respect to the CNE principles.

As acquired from the literature summary, CNE is based on strategies known as reducing, narrowing, closing, slowing, and regenerating (Velasco-Muñoz, et al., 2021; Morseletto, 2020). Reducing food waste and consumption by changing diets in high-income countries to a healthy level of nutritional needs (Papargyropoulou et al., 2014), are recognized as essential strategies to avoid waste at the consumption stage (Muscat et al., 2021). At the production stages, according to Velasco-Muñoz et al. (2021), narrowing should refer to practices that aim to use resources more efficiently to avoid nutrient leakage. Furthermore, closing stands for the reuse of agricultural materials, such as feeding livestock with crop residues. Closing is a strategy like cascading, a synonymous term from CE concepts, where biological materials go through multiple uses before becoming non-toxic organic unavoidable waste (Morseletto, 2020). Slowing in nutrient cycles means, for example, extending the lifetime of food through preservation alternatives (Velasco-Muñoz, et al., 2021). Similarly, to preserve the biomass as long as possible, inedible organic waste such as faeces or food waste can be upcycled by insects (e.g., Black Soldier Fly), rather than being composted or digested for energy recovery.

Particularly in agriculture, the mentioned strategies overlap between themselves. This means that the implementation of one strategy affects the outcome of another: where, for example, reducing biomass extraction influences strategies for closing local nutrient cycles, since reducing resource consumption indirectly leads to less production of waste streams (Velasco-Muñoz, et al., 2021).

In the hierarchy analysis framework (Table 4) natural constraints and intrinsic flows are considered, especially aspects of regeneration (Navare et al., 2021), value-added prioritization (Velasco-Muñoz et al., 2021), closing and cascading of biomass (Navare et al., 2021), hazard substances bioaccumulation (McConville et al., 2015), and agricultural land use competition (Muscat et al., 2020).

The framework of Table 3 allows to integrate qualitative aspects (Aznar-Sánchez et al., 2020), while also including a hierarchy perspective.

Table 4. The hierarchy analysis framework for CNE strategies of a typical regional nutrient economy summarized for each subsystem (modified from McConville et al. (2015)).

Subsystem / CNE strategy	Priority	Crop production	Livestock production	Food and feed processing	Consumption	Waste management
Reduce		• *Improve fertilizer efficiency* • *Reduce mineral / chemical applications* • *MAX regenerative farming*	• *Recouple LK with crop production* • *Align LK size with local ML capacity* • *Restrict ENC to ML surplus, avoiding LK resource competition* • *Reduce nutrient rich feed imports* • *MAX regenerative farming*	• *Reduce OW production* • *Avoid harmful chemicals* • *Limit nutrients in food additives*	• *Reduce OW production* • *Reduce ASF consumption* • *Buy less goods with additives*	• *Reduce OW production* • *Prevent upstream contamination* • *MAX separate OW streams*
Reuse		• *Reuse residuals for fodder*	• *Reuse manure on local fields, if in excess export to neighbouring farms*	• *Reuse nutrient rich waste for food / fodder*	• *MAX OW separation*	• *Reuse organic rich materials*
Recycle		• *Crop residuals AD ER to farm* • *Crop residuals to the soil*	• *Manure AD ER to farmland* • *Reuse manure locally*	• *Convert to new biochemicals* • *AD ER to farm* • *AD ER to landscape* • *Compost to farm* • *Compost to landscape*	• *Buy more recovered / organic items* • *Recycle OW at home*	• *AD ER to farm* • *AD ER to landscape* • *Compost to farm* • *Compost to landscape*
Recycle		• *Residuals AD ER to farm* • *Residuals to the soil*	-	• *Convert to new biochemicals* • *AD ER to farm* • *AD ER To landscape* • *Compost to farm* • *Compost to landscape*	-	• *AD ER to farm* • *AD ER to landscape* • *Compost to farm* • *Compost to landscape*
Incineration		-	-	• *ER*	-	• *ER*
Disposal		-	-	• *Landfill*	-	• *Landfill*

ENC: energy crops; LK: livestock; ML: marginal land; OW: organic waste; MAX: maximize; ASF: animal sourced food; AD: anaerobic digestion; ER: energy recovery

3.2 Development of a new set of circularity indicators

For all four biological regions under study, the 4R framework is applied to better understand sustainable nutrient management. This should give a figure of how well regions are reducing virgin sources, minimizing losses, and increasing reuse practices. In material reuse, cascading (up- or downcycling) is achieved by prioritizing organic waste material integrity over reuse practices where biomass degrades more rapidly. AD energy recovery from organic waste streams should be enabled, if technically and economically feasible, and especially prioritized over incineration and disposal. The hierarchical concepts which are integrated in the Phosphorous Output Circularity Index (POC_{index}) evaluate circularity performance by giving an ABCD-class score that figures the system performance in reducing, reusing, maximise or minimize nutrient use, while additionally also evaluating safety, energy benefits and transportation costs. This indicator has been deemed necessary to develop, given that regional assessments should be able to simplify complex systems into manageable information (Saidani et al., 2019) and because Circularity should be prevented from becoming a synonymous term for Recycle (Pires & Martinho, 2019). In addition to POC_{index}, the regeneration of agricultural and natural capital has been addressed (organic P input share), and overproduction limited (SLU_{dev}).

3.2.1 P Output Circularity Index (POC_{index})

The first indicator proposed in this study is the POC_{index} which, is inspired by the formula of Pires et al. (2019) and gives a final score to the waste management subsystem in form of classes ranging from A to D. The attribution of a class expresses, according to the objectives of CNE in agro-food-waste nutrient cycles (Table 3), how positive or negative the P-organic waste flows after consumption are reintroduced in the agri-food-waste system. The goal of POC_{index} is to assess following six CNE objectives:

1. **Safety**: the degree of separation from technical contaminated cycles (Isenhour et al., 2022)
2. **Loop**: the efficiency of farm versus landscape cycling (Navare et al., 2021),
3. **Cascading**: the level of cascading treatment technology involved (Valve et al., 2020), the level of cascading hierarchy between upcycling or downcycling (Papargyropoulou et al., 2014), the soil conditioning benefits (Hermann et al., 2011), and the fertilizer's best $NH4^+$ plant availability (Valve et al., 2020)
4. **Energy**: the energy recovery contribution (Moraga, et al., 2019) from AD or incineration
5. **Losses**: the overall degree of losses of the waste management practices (Navare et al., 2021)
6. **Transportation costs**: high or low costs for reuse of fertilizer (this was included to show that potentially also economic or social CNE aspects can be added when applying this method)

With a common regional MFA various flow can be described. In this study flows used for the POC_{index} have the unit of P t a^{-1} and are originating from consumption subsystems (organic or mixed consumption) to productive or other end-subsystems: landscape, private backyards, landfill, and environment (Figure 3).

In a MFA several flows (X_1, X_2, X_3, X_4, ...) can be identified, and in general they can be distinguished into recovered, recycled, disposed or as lost. The POC_{index} is built on a formula with weighting factors (*k_i-values*) for each flow (X_i), calculated in relationship to the total organic waste and losses flows produced after consumption ($\sum_{i=1}^{Nf} X_i$) (equation 1).

$$POC_{index} = \frac{\sum_{i=1}^{Nf} k_i X_i}{\sum_{i=1}^{Nf} X_i} \times 100 \qquad (1)$$

A POC_{index} of 100 indicates the highest possible recirculation quality, while an index of 0 indicates the worst possible scenario. To define k_i-values, each flow is given a sum of points between 0-600, this since with six objectives, each flow can have a maximum of 600 points (P_{total})(Table 5).

To calculate k_i, the resulting points (P_{X_i}) for each flow X_i are divided by $P_{X_{total}}$ as shown in equation 2. This allows to rank A, B, C, and D classes depending on k_i values, with each class having a set of recurring characteristics (Table 6).

$$k_i = \frac{P_{X_i}}{P_{X_{total}}} \qquad (2)$$

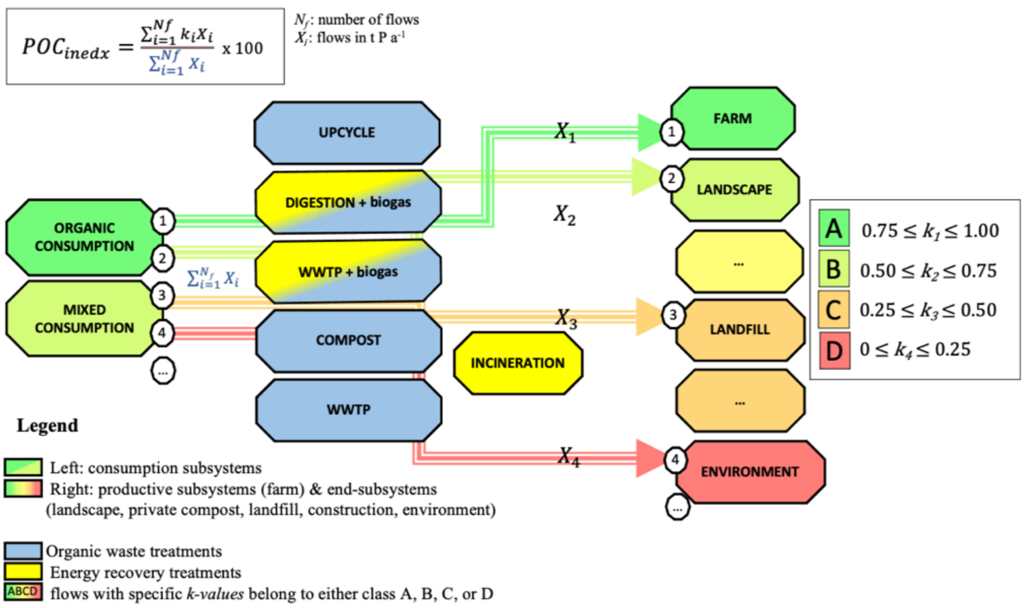

Figure 3. Theoretical representation of sub-systems and flows considered to apply the POC_{index}. In this specific case flows consider P t a^{-1}, however it could be applied to any other macronutrient (N, K).

As shown in Table 5, the distribution of the points depends on the number of contributions applied. For example, *Losses* presents two types of contributions, which gives two scores (100 = positive and 0 = negative), while *Safety* presents instead three (100 = positive, 50 = neutral, 0 = negative).

To the best of the author's knowledge, there is no consensus as to which organic waste streams are more beneficial from a CNE perspective when used for landscaping or farm applications. However, in this study it is argued that landscaping should be considered as a less valuable closing strategy because ultimately it does not produce food, as food production is the highest priority (Muscat et al., 2020). To address the hierarchical difference in recovering nutrients for gardening or food production, it was decided to allocate fewer points to the landscape application in *Loop* objective (L_p = 75, Table 5), while farm reuse gets the highest score (L_p = 100, Table 5).

Regarding *Safety* objective, the flows can be distinguished into *source separated organic waste* (S_a = 100) and *mixed organic waste* (S_a = 50), the first gaining higher score since less if not contaminated than the latter.

Table 5. To calculate individual k_i-values, every flow is evaluated by giving a score between 0-100 for each objective (P_{total} = 600).

Objective	Description	Points in relation to the specific CNE contributions					
Safety	*Safety for application depends on separation performance and on organic residues' origin*	100		50			0
		source separated organic waste only originated from organic sourced consumption		mixed organic waste (organic + conventional products)			no collection of material
Loop	*Best loop option to reduce virgin input & closing*	100		75	25		0
		material reused on farm		material reused for landscape	material reused for private gardening		material not reused
Cascading	*Cascading, regeneration, best treatment, and application options for agriculture reuse*	100	80	60	40	20	0
		upcycled into new (feed) products	downcycled	downcycled	downcycled	downcycled	landfilled
			reused as fertilizer	reused as fertilizer	reused as fertilizer		
			soil benefits	soil benefits			
			better NH_4^+ plant availability				
Energy	*best energy option by avoiding material degradation*	100		75	25		0
		biogas production		biogas production at WWTP	heat production from incineration plant		no energy production involved
Losses	*reduce losses & eutrophication*	100			0		
		safely recovered material			environmental losses		
Transportation costs	*Costs are generally affected by the water content of materials*	100		50			0
		no additional costs for reuse purposes		lower transportation costs for reuse because of "lighter" material			bulky materials: higher transportation costs for reuse

Flows that cascade better according to the hierarchy analysis framework for CNE strategies are the ones that are upcycled into new products and score of C_a = 100 (Table 5 & 7, *Cascading*). If flows are downcycled, for example digestate from AD, it counts as reused as fertiliser, it is beneficial for the soil, and is more beneficial from a N perspective since NH_4^+ would be more plant available (Valve et al., 2020). This specific flow would result in a score of C_a = 80 (Table 5 & 7, *Cascading*).

To show an example of upcycled (value-added) material, the two flows (flow nr. 3 and flow nr. 8), which are organic and mixed sourced waste treated with BSF and applied on farm, have been added to the theoretical POC_{index} list of flows (Table 7), even though there are no flows of this kind in current MFA case studies yet.

From an *Energy* perspective in biogas production, it does not matter if the digestatel is contaminated or not, the energy produced will be the same. However, two different scores are given: biogas production at WWTP is assumed to deliver mixed contaminated materials to the farm (E_n = 75), while biogas production at farm level is assumed to have no contamination from urban sources (100 points).

Objective *Losses* is better explained with an example: if 100 kg P organic compost are transported to the farm (flow nr. 11, *ORG compost to farm,* Table 7) and 1 kg P is lost to the environment on the way (flow nr. 24, *Uncollected*, Table 7) than these account as two separate flows with different k values. The first one of 99 kg would have 360 points and the second flow of 1 kg a score of 100 points.

Regarding *Transportation costs*, each flow has different benefits in terms of Transport. For example, the outflow at the WWTP (nr. 25) does not generate transportations costs (T_c = 100, Table 5). But if sludge is brought to construction sites (flow nr. 27) then it generates costs, and thus it gets a score of T_c = 0. Furthermore, materials that enrich soils by adding organic fertiliser are heavier than mineral fertilizer because of higher water content and will always generate higher transportation costs. For example, flow nr. 1 (*ORG digestate to farm + AD energy*, Table 7) has as major negative contribution the fact of being heavy to transport (T_c = 0, Table 5). On the other hand, "lighter" materials include struvite or BSF, for example, where water content is reduced but are both originated from an organic waste treatment plant.

Table 6. The four classes with their main features and index scores (0 ≤ POC_{index} ≤ 100)

Class	Objective	Flows predominant characteristics	k_i	POC_{index}
A	1	organic sourced materials	0.75 - 1	**75 - 100**
	2	reuse on farm		
	3	optimal downcycling and upcycling		
	4	biogas recovery with mainly uncontaminated materials		
	5	zero losses		
	6	higher transportation costs		
B	1	mixed sourced materials	0.50 - 0.75	**50 - 75**
	2	reuse for landscape purposes (gardening)		
	3	moderate downcycling		
	4	moderate to zero energy recovery		
	5	zero losses		
	6	lower transportation costs		
C	1	mixed sourced materials	0.25 - 0.50	**25 - 50**
	2	reuse for landscape or landfill		
	3	low downcycling efficiency		
	4	mainly incineration with heat recovery		
	5	zero losses		
	6	higher transportation costs		
D	1	mixed sourced materials and uncollected flows	0 - 0.25	**0 - 25**
	2	no reuse		
	3	no recycling		
	4	no energy recovery		
	5	moderate to high material losses		
	6	lower or no transportation costs for reuse		

When objectively applying this ranking method to the most common flows found in regional MFAs for P, the resulting POC_{index} classes are shown in Table 7, where class A presents 3 flows, (1-3), class B presents 13 flows (4-16), class C presents 7 flows (17-23), and class D has 4 flows (24-27). Details regarding the number of points and k-values for each flow are shown in Table 7.

Table 7. Twenty-seven theoretical organic waste flows have been identified (ORG = organic waste sourced from organic production, S_a = safety, L_p = loop, C_a = cascading, E_n = energy, L_o = losses, T_c = transportation costs)

Nr.	**flow characteristics**	**S_a**	**L_p**	**C_a**	**E_n**	**L_o**	**T_c**	total points	*k*-value	**POC_{index} classes**
1	*ORG digestate to farm + AD-energy*							480	*0,80*	**A**
2	*ORG digestate to landscape + AD-energy*							455	*0,76*	
3	*ORG BSF to farm*							450	*0,75*	
4	*Struvite to farm + AD-WWTP-energy & heat*							440	*0,73*	**B**
5	*Digestate to farm + AD-energy*							430	*0,72*	
6	*Digestate to landscape + AD-energy*							405	*0,68*	
7	*Sludge to farm + AD-WWTP-energy*							405	*0,68*	
8	*BSF to farm*							400	*0,67*	
9	*Sludge to landscape + AD-WWTP-energy*							380	*0,63*	
10	*Struvite to farm + heat*							365	*0,61*	
11	*ORG compost to farm*							360	*0,60*	
12	*Private green waste*							335	*0,56*	
13	*Private compost*							335	*0,56*	
14	*ORG compost to landscape*							335	*0,56*	
15	*Compost to farm*							310	*0,52*	
16	*Sludge to farm*							310	*0,52*	
17	*Compost to landscape*							285	*0,48*	**C**
18	*Sludge to landscape*							285	*0,48*	
19	*Sludge + AD-WWTP-energy & heat*							250	*0,42*	
20	*Sludge to construction + AD-WWTP-energy*							245	*0,41*	
21	*ORG biowaste + heat*							225	*0,38*	
22	*Biowaste + heat*							175	*0,29*	
23	*Sludge + heat*							175	*0,29*	
24	*Uncollected*							100	*0,17*	**D**
25	*Outflow WWTP*							100	*0,17*	
26	*Erosion from urban soils*							100	*0,17*	
27	*Sludge to construction*							70	*0,12*	

3.2.2 SLU_{dev}

To address *criterium 2*, the biophysical constraints, it was decided to focus on livestock production.

Feeding livestock only with local grasslands is primarily limited by the extent of grassland availability, and by the type of human diet (Van Zanten et al., 2018).

An effective way to manage grasslands would be to limit meat production to the regional context, ensuring protein supply while maintaining the diversity of the landscape. In addition, the role of livestock in CNE is crucial for recycling agricultural waste, food waste, and organic residues while producing manure that can be used for organic crop production (Van Zanten et al., 2018).

A way of measuring the soil biophysical constraints is using the Muencheberg Soil Quality Rating (M-SQR), which allows to determine various soil scores ranging between 0 and 100, were soils with 100 present optimal conditions for crop production (Gerwin et al., 2018).The M-SQR includes 8 basic indicators (such as substrate, topsoil structure, compaction, or relief) and 12 hazard indicators (such as contamination, thermal regime, salinization, flood risk, etc.). This method has been used especially in the context of bioenergy production, were soils with M-SQR < 40 have been considered as marginal land that is not suitable for crop production and would therefore open up secondary land use options (Gerwin et al., 2018).

The Standard Livestock Unit deviation factor (SLU_{dev}) developed here (equation 3) serves as an indicator of livestock production efficiency within a given region. It is calculated by dividing the actual number of SLU units present in the region (SLU_{actual}) by the SLU production potential (SLU_{pot}). The SLU_{pot} represents the potential number of livestock that could be produced if ruminants were fed exclusively with grassland resources from local marginal lands.

$$SLU_{dev} = \frac{SLU_{actual}}{SLU_{pot}} \qquad (3)$$

If $SLU_{dev} > 1$, it means that SLU_{actual} exceeds the regional marginal land capacity to feed ruminants on locally available marginal land resources. On the other hand, $SLU_{dev} < 1$ means that the regional grassland capacity is not fully utilized.

3.2.3 Share of organic P inputs

To address the issue relative to *criterium 3*, the invisible toxicants such as herbicides and chemicals that can be applied at the upstream stages of production in farm systems, and if CNE is to become regenerative and safe at all stages, the most efficient way for safer and regenerative waste management is to tackle the contamination issues at source rather than after the consumption stage (Isenhour et al., 2022). In general terms, agricultural activities that produce crops and feed for livestock can be either organic or conventional. By knowing the share of organic P input, one can have an insight regarding the quality and safety of the collected organic waste.

Within the EU, organic farming methods are regulated by EEC Regulation No. 2078/92 and neither mineral fertilizers nor synthetic pesticides are allowed (Gabriel et al., 2010). Organic licensed farming is therefore used as a proxy indicator for uncontaminated food and feed products entering the food system.

3.3 Application of developed circularity indicators

3.3.1 MFA case studies

To make an evaluation of the POC_{index} effectiveness, a series of MFA-P flows were extrapolated from four different MFA-P studies found in literature (Appendix 1), all located in Europe. The first data set is from Denmark (Klinglmair et al., 2017), secondly the Brussel capital region (Papangelou et al., 2020), the national border of Switzerland (Mehr et al., 2018), and at last the Brandenburg-Berlin region (Theobald et al., 2016).

Denmark

Klinglmair et al. (2017) conducted a regional study of the phosphorus (P) budget in three regions of Denmark, analysing detailed P flow information at the waste management subsystem level. For the study the region around Copenhagen was selected for application, which was defined as region A in Klinglmair et al. (2015). The region around Copenhagen has a population of around 2.5 million and a total geographical area of 9,834 km², 57% of which is used for agriculture (Klinglmair et al., 2015).

Brussel region

The second dataset used was provided by Papangelou et al. (2020) and comprises an MFA analysis of P-flows for the Brussels Capital Region. This region has a population of approximately 1.1 million and covers an area of 161 km² (IBSA, 2015). Unlike the other three regions, it has no agricultural land, accounting for only around 1% of the total area (Papangelou et al., 2020), which is therefore neglectable.

Switzerland

The third region comes from Mehr et al.'s (2018) study of the national phosphorus budget in Switzerland. This region covers an area of 41,285 km² and had a population of around 8.5 million in 2018. Due to the presence of the Alps, only 21% of the total geographical area can be used for agriculture. It was estimated that 39% of the agricultural area was used as cropland and 61% as grassland (Stumpf et al., 2018).

Brandenburg-Beriln

The last region is Brandenburg, in Germany from the study by Theobald et al. (2016). The population in Berlin-Brandenburg is about 3.5 million inhabitants (Zasada et al., 2019). Brandenburg consists of 14 municipalities and surrounds the national capital Berlin with a total geographical area of 29,478 km^2, of which 45% are used for agricultural production (Tavakoli-Hashjini et al., 2020).

Crop production appears to be challenging due to low rainfall and the fact that two-thirds of the soils are sandy or sandy loamy with low water-holding capacity (Gutzler et al., 2015).

3.3.2 POC_{index} assumptions and MFA-P data acquisition

Many assumptions and estimations have been made since data on the flows was difficult to find. As can be seen in Table 8, few flows have actually been found, except in the Brandenburg region, which is well covered (see Table 8).

In the case of Brussel region, the fate of WWTP sludge is unknown (exported volume = 563 t P/a), thus in this study this flow was assumed to be incinerated and landfilled and therefore accounted as which. In the study of Mehr et al. (2018) for the Swiss region, it was not specified how much digestate and compost was recycled, so it was assumed that of the total (1237 t P/a), 50% was composted and 50% digested.

Table 8. From the four regions twenty-seven theoretical flows were found. If not available, the flows were not added (n.d.) or in some cases estimated (in bold). Values are in t P a^{-1}.

Flow (route)	Denmark	Brussel	Switzerland	Brandenburg
ORG digestate to farm + AD-energy	n.d.	n.d.	n.d.	n.d.
ORG digestate to landscape + AD-energy	n.d.	n.d.	n.d.	n.d.
ORG BSF to farm	n.d.	n.d.	n.d.	n.d.
Struvite to farm + AD-WWTP-energy & heat	n.d.	n.d.	n.d.	**2,1**
CONV digestate to farm + AD-energy	n.d.	2,0	**618,5**	**4,5**
CONV digestate to landscape + AD-energy	n.d.	n.d.	n.d.	**71,5**
Sludge to farm + AD-WWTP-energy	n.d.	n.d.	n.d.	**47,2**
CONV BSF to farm	n.d.	n.d.	n.d.	nd
Sludge to landscape + AD-WWTP-energy	n.d.	n.d.	n.d.	**67,2**
Struvite to farm + heat	n.d.	n.d.	n.d.	**13,9**
ORG compost to farm	n.d.	n.d.	n.d.	n.d.
Private green waste	n.d.	n.d.	n.d.	90,0
Private compost	n.d.	n.d.	34,0	53,0
ORG compost to landscape	n.d.	n.d.	n.d.	n.d.
CONV compost to farm	n.d.	5,0	**618,5**	4,5
Sludge to farm	1200,0	n.d.	n.d.	**315,8**
CONV compost to landscape	**410,0**	11,0	n.d.	**71,5**
Sludge to landscape	n.d.	n.d.	n.d.	**449,8**
Sludge + AD-WWTP-energy & heat	n.d.	n.d.	n.d.	**341,8**
Sludge to construction + AD-WWTP-energy	n.d.	n.d.	n.d.	**8,1**
ORG biowaste + heat	n.d.	158,0	n.d.	n.d.
CONV biowaste + heat	n.d.	n.d.	n.d.	675,0
Sludge + heat	4,0	**563,0**	6854,0	**2287,2**
Uncollected pet excrements	n.d.	58,0	20,0	148,0
Outflow WWTP	100,0	139,0	935,0	334,0
Erosion from urban soils	n.d.	n.d.	n.d.	163,0
Sludge to construction	n.d.	n.d.	2746,0	**53,9**

In the study of Denmark, it was assumed that the exported compost (410 t P/a) flow was used for landscape application out of the system boundary (SB), so it was interpreted as "reused", even if it did not take place inside the SB (see Appendix 1). For Denmark, Brussel capital and Switzerland it was assumed that at the WWTPs no AD-energy was produced. Because of the value-added aspect of recovering energy (CNE objective 8), it makes a difference if sludge for example is recovered from a WWTP that also produces energy, and so it was necessary to distinguish between WWTP with AD and WWTP without. In Germany, 87% of biogas plants operate with agricultural feedstock, while only 11% are located at WWTP using sewage sludge (Torrijos et al., 2016). Considering this, it was decided to estimate how many digesters are located on WWTPs (only in Brandenburg).

In Germany, there are 1274 WWTPs with AD (Nguyen et al., 2021) out of a total of about 10,000 plants (BMUV, 2024), which means that on average 13% of WWTPs in Germany are equipped with biogas plants. It was therefore assumed that in Brandenburg 13% of sludge outputs from WWTP are digested providing energy prior to farm/landscape reuse.

Since up to date there is no practical example nor method to separate biowaste into organically sourced and conventionally sourced fractions, for the following application all flows are assumed to be conventionally sourced, meaning that they are all considered as mixed materials.

Lastly, in Brandenburg the flow “composted biowaste” to farmland (9 t P a^{-1}) and “soil conditioner” to urban areas (143 t P a^{-1}) from centralized composting entails also digestate from urban AD treatment (Theobald et al., 2016). Since it is not known how much is digested and how much is composted, it is assumed that 50% is digested providing energy recovery and 50% only composted.

3.3.3 Circularity

In addition to the hierarchical output assessment with POC_{index} for all regions proposed in this study, it was decided to apply a circularity indicator found in the literature: the C indicator developed by Tanzer et al. (2020), which uses a method where the quantitative value of recycled materials determines the degree of system circularity.

C is constructed as shown in equation 4 by calculating the sum of recycled materials (manure, digestate, construction, compost, etc.) divided by the sum of flows that occur in the whole system (throughput), such as recycled materials, net imports, net exports, emissions to the environment, and accumulation in stocks (e.g. landfills, soils, urban areas, etc.):

$$C = \frac{recirculated\ mass}{system\ throughput} \times 100 \qquad (4)$$

With C, a value between 0-100 can be calculated, where 100 is the highest circularity, as all flows would be recirculated. This method considers all flows of each subsystem: production, consumption, and waste management.

3.3.4 SLU_{dev} data acquisition and assumptions

The Muencheberg Soil Quality Rating (M-SQR) earlier described, was taken for Brandenburg from a study of Tavakoli-Hashjini et al. (2020), who estimated that 55% of the arable land has very good to moderate characteristics for food crop production (M-SQR > 40) and that on the other hand 45% can be considered as marginal land (M-SQR < 40), which could be suitable for forage production or energy crops. Since no M-SQR scores have been found for the other three regions, for Denmark, Brussel, and Switzerland, instead, Gerwin et al. (2018) estimated that around 10% of agricultural land in Europe is potentially available to use as marginal land for biomass production.

Data for SLU_{actual} (including number of cattle, mother cows, dairy cows, and sheep) in the four regions were taken from the local statistical offices for Brandenburg and Switzerland, while EUROSTAT data was taken for Belgium and Denmark (Amt für Statistik Berlin-Brandenburg (2024); Trading Economics (2023); Bundesamt für Statistik (2023)). Chickens, hens, and pigs were not included because these animals do not primarily feed on grassland (Van Hal et al., 2019).

To calculate the SLU_{pot} one needs to estimate how much marginal land in hectares is available. To know how much one SLU consumes in a year it was considered that for ruminants, on average, one SLU consumes 4,571 kg of Dry Matter (DM) grassland a^{-1} (Qi et al., 2023). The average herbal yield on grassland in the UK on rough grazing surfaces (low productivity) is in average 2.76 t DM ha^{-1} (Qi et al., 2023), which is assumed to be similar for all four regions.

According to the estimations by Qi et al. (2023), each Standard Livestock Unit (SLU) needs to feed on 0.6 ha $a^{-1}$of grassland.

As in this study food production is given a higher priority than energy production, it is assumed that of the available marginal land, 75% of it should be used as ruminant feed and 25% for bioenergy production.

3.3.5 Assumptions and data acquisition for the share of organic P inputs

The ratio of organic P masses is calculated in relation to the total input flows for each region (sum of imports + sum of production). To calculate the organic fractions of production and in market retail, the region's specific shares of organic agriculture were used to determine the organic P inputs to consumption. Shares of organic production for each region were taken from IFOAM & FIBL (2023).

The P masses of imported feed & animal products are assumed to be contaminated (0% organic share). This was deemed necessary because of the impossibility of extrapolate information about external farm practices.

4. Results

4.1 P Output Circularity Index (POC_{index})

Figure 5 displays the calculated POC_{index} values for Brandenburg, Denmark, Switzerland, and Brussels, which are 34, 49, 27.6, and 28.4, respectively. Along with the POC_{index} values, the types and distribution percentages of the flows are also illustrated (Figure 4).

For Brandenburg 20 flows are identified and calculated, while Denmark, Switzerland, and Brussels have 4, 6, and 7 flows, respectively. In Brandenburg, Switzerland, and Brussels, the largest flow category is "*Sludge + heat*," flow number 23, accounting for 44%, 58%, and 60.1% of the total flows, respectively (Figure 4). In Denmark, the most significant flow identified is "*Sludge to farm*," which represents 70% of the total (flow nr. 16).

All regions are classified as category C, with Denmark having the highest score, nearly reaching category B (POC_{index} = 50-75) (Figure 4). In contrast, Switzerland and Brussels were close to being classified as category D, as their POC_{index} values were near the threshold value of POC_{index} = 25

4.2 Circularity

The flow values (tP a^{-1}) are sourced from the original MFAs studies (Appendix 1). A circularity assessment is presented for each region (Table 8). Brandenburg exhibits a circularity level of C = 44.5, which ranks second only to Switzerland (C = 50.1). Notably, Brandenburg's data had the highest resolution among the regions, with 9 flows classified under *Recirculated Mass* and 26 flows included in the *System Throughput* (Table 8). Region A in Denmark has a Circularity level of C = 28.7, the Brussels-Capital region shows a circularity of just C = 1.4, and Switzerland leads with a circularity level of C = 50.1.

In Denmark, only two flows, *Sludge and Manure*, were identified as part of the *Recirculated Mass*. By contrast, both Brussels and Switzerland recorded four flows contributing to their *Recirculated Mass*.

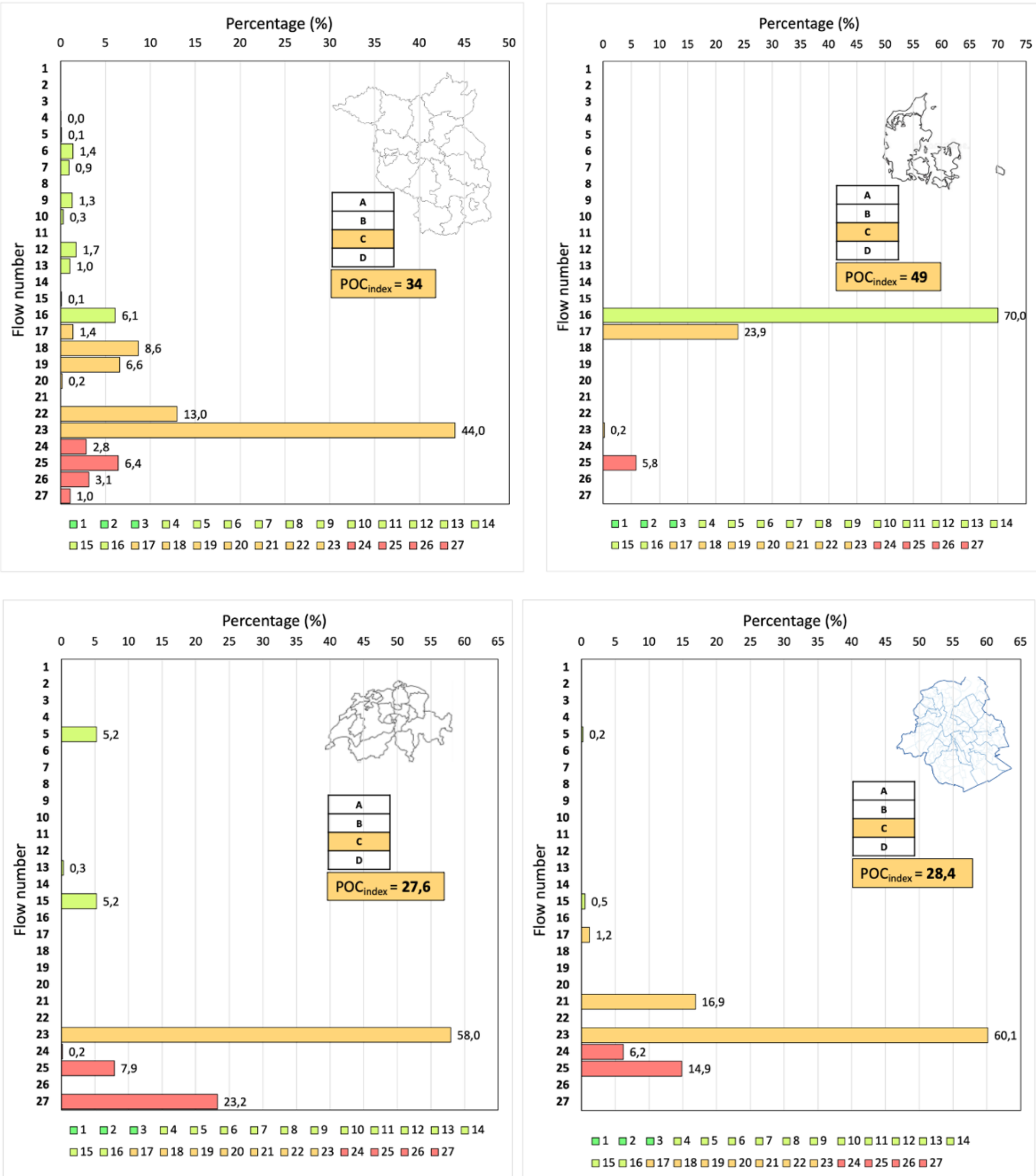

Figure 4. The distribution of the reused and lost organic waste containing P flows (in t P/a) in Brandenburg-Berlin (top, left), region A of Denmark (top, right), the national borders of Switzerland (bottom, left) and the Brussel capital region (bottom, right). Of the 27 theoretical flows defined in the POC_{index} method, only Brandenburg had a satisfactory number of flows. The same could not be said for the other regions.

Table 9. Flows used to calculate circularity (C) using the method proposed by Tanzer et al. (2020)

Region	*Flow Type*	$t\ P\ a^{-1}$	*Recirculated Mass*	$t\ P\ a^{-1}$	*System throughput*	***C** (%)*
Brandenburg Berlin	Recycling	3734	Residuals	3734	Residuals	***44,5***
		9146	Manure	9146	Manure	
		2490	Digestate	2490	Digestate	
		16	Struvite	16	Struvite	
		363	Sludge	363	Sludge	
		9	Composted biowaste	9	Composted biowaste	
		143	Soil conditioner	143	Soil conditioner	
		62	Sludge construction	62	Sludge construction	
		517	Sludge landscaping	517	Sludge landscaping	
	Import			149	Sludge	
				4477	Synthetic fertilizer	
				2648	Soja cake & forage	
				460	Livestock	
				975	Processing	
				3512	Goods	
	Export			2703	Feed	
				739	Livestock	
				926	Processing	
				1703	Animal products	
				1499	Slaughter waste	
	Emissions			1051	Erosion	
				163	Erosion	
				334	Outflow WWTP	
	Stocks			-3617	Stock farm	
				175	Urban areas	
				2629	Landfill	
Region A Denmark	Recycling	1200	Sludge	1200	Sludge	***28,7***
		6600	Manure	6610	Manure	
	Import			640	Synthetic fertilizer	
				6610	Feed	
				2380	Food	
	Export			410	Compost	
				9100	Food & feed	
				190	Environmental losses	
	Emissions			100	WWTP Outflow	
				20	Losses crops	
	Stocks			20	Waste management	
				-110	Stock soil	
Brussel capital	Recycling	11	Compost	11	Compost	***1,4***
		10	Green waste	10	Green waste	
		5	Compost	5	Compost	
		2	Digestate	2	Digestate	
	Import			195	Non-food	
				694	Food	
				15	Wastewater (WW)	
				106	WW Flanders	
	Export			563	Sludge	
				55	Crops	
				164	Ash	
	Emissions			139	Outflow WWTP	
Switzerland	Recycling	23353	Manure	23353	Manure	***50,1***
		1237	Digestatet + compost	1237	Digestatet + compost	
		66	Waste paper	66	Waste paper	
		2746	Cement plant	2746	Cement plant	
	Import			4229	Synthetic fertilizer	
				2198	Food	
				1234	Cleaning products	
				360	Chemicals	
				6222	Fodder	
				501	Animal-based food	
	Export			4	Living animals	
				69	Wood paper	
				2418	Animal byproducts	
				134	Ash	
				106	Sewage sludge	
	Emissions			745	Outflow WWTP	
				190	Stormwater	
				1136	Agricultural erosion	
				20	Excrements leachate	
	Stocks			6490	Landfill D	
				454	Landfill C	
				323	Forest	
				456	Soils	
				34	Gardens	

4.3 SLU deviation factor (SLU_{dev})

The total agricultural area in Brandenburg is 1,326,510 ha, of which 596,929.5 ha are classified as marginal land. If 75% of the marginal land is used as ruminant feed, in Brandenburg there would be 447'697 ha available for livestock feeding (Table 10). Based on this, the SLU_{pot} would be 268,618 SLU. The actual livestock population in Brandenburg in 2016 was 880'500 (SLU_{actual}). This results in a SLU_{dev} = 3.3, indicating that the local grassland resources are insufficient to support the current ruminant-livestock population density.

For Denmark the SLU_{dev} = 6.8 is slightly higher than Brandenburg. On the other hand, Belgium and Switzerland have a much higher range of values, 33.1 and 30.3, respectively.

Table 10. SLU_{dev} values for the four regions considered in this study

Region		***Tot. agricultural area***	***Marginal land***	***75 % of Marginal land***	***SLU_{pot}***	***SLU_{actual}***	***SLU_{dev}***
	Unit	ha	ha	ha	Nr	Nr	0 < 1 < ∞
Brandenburg		1'326'510	596'929	447'697	268'618	880'500	**3,3**
		Tavakoli-Hashjini et al. (2020)	*Tavakoli-Hashjini et al. (2020)*		*calculated*	*Amt für Statistik Berlin-Brandenburg (2024)*	
Denmark		2'620'947	262'094	196'571	117'942	797'070	**6,8**
		Statistics Denmark (2023)	*Gerwin et al. (2018)*		*calculated*	*Trading Economics (2023)*	
Belgium		594'274	59'427	44'570	26'742	885'850	**33,1**
		Statbel (2024)	*Gerwin et al. (2018)*		*calculated*	*Trading Economics (2023)*	
Switzerland		1'445'185	144'518	108'388	65'033	1'973'000	**30,3**
		BFS (2024)	*Gerwin et al. (2018)*		*calculated*	*BFS (2023)*	

4.4 Share of organic P inputs

Table 11 presents the shares of organic and conventional inputs from the different food sources for the four regions. The organic inputs are calculated by multiplying the organic share with the total input. In Brandenburg, Denmark, Brussel, and Switzerland, the proportion of inputs sourced organically are 9,4%, 7,2%, 3,7%, and 14,3%, respectively.

Table 11. Flows used for the calculation to estimate the share of organic sourced P inputs in the four regions. Organic shares are taken from IFOAM & FIBL (2023).

Region	**Flows**	**Inputs**	**Organic inputs**	**Conventional inputs**	**Organic share**	**Sector**
	Description	tP a^{-1}	tP a^{-1}	tP a^{-1}	%	
Brandenburg	Feed import	2648,0	0,0	2648,0	0	Import
	Livestock import	460,0	0,0	460,0	0	Import
	Processing import	975,0	61,4	913,6	6,3	Retail Market
	Goods purchase	3512,0	221,3	3290,7	6,3	Retail Market
	Regional crops uptake	19017,0	2129,9	16887,1	11,2	Production
	Regional forage production	4125,0	462,0	3663,0	11,2	Production
	total	*30737,0*	*2874,6*	*27862,4*		
	%	**100,0**	**9,4**	**90,6**		
Denmark	Feed import	6610,0	0,0	6610,0	0	Import
	Livestock import	no data	0,0	0,0	0	Import
	Processing import	no data	0,0	0,0	12,0	Retail Market
	Goods purchase	2380,0	285,6	2094,4	12,0	Retail Market
	Regional crops uptake	1840,0	211,6	1628,4	11,5	Production
	Regional forage production	6610,0	760,2	5849,9	11,5	Production
	total	*17440,0*	*1257,4*	*16182,7*		
	%	**100,0**	**7,2**	**92,8**		
Brussel	Feed import	no data	0,0	0,0	0	Import
	Livestock import	no data	0,0	0,0	0	Import
	Non-food import	195,0	7,2	187,8	3,7	Retail Market
	Food products	694,0	25,7	668,3	3,7	Retail Market
	Regional crops uptake	no data	0,0	0,0	7,4	Production
	Regional forage production	no data	0,0	0,0	7,4	Production
	total	*889,0*	*32,9*	*856,1*		
	%	**100,0**	**3,7**	**96,3**		
Switzerland	Feed import	6222,0	0,0	6222,0	0	Import
	Animal based food import	501,0	0,0	501,0	0	Import
	Plant based food import	2108,0	236,1	1871,9	11,2	Retail Market
	Goods purchase	no data	0,0	0,0	11,2	Retail Market
	Plant based food production	3751,0	671,4	3079,6	17,9	Production
	Regional forage production	25187,0	4508,5	20678,5	17,9	Production
	total	*37769,0*	*5416,0*	*32353,0*		
	%	**100,0**	**14,3**	**85,7**		

5. Discussion

5.1 Application of developed indicators

This chapter focuses on the evaluation of the indicators that were developed in this study: the POC_{index}, SLU_{dev}, and the share of organic P inputs. These indicators provide a novel approach to system analysis within regional context in CNE. Unlike previous indicators, these metrics are designed to offer a simpler yet effective framework for analysis, which focuses on the hierarchization, the livestock production in relation to biological limits, and the regional regenerative and contamination risks.

Using P as a proxy for biological materials rather than C, N or K can be a promising approach due to its binding nature with biomass, its accumulation in soils and its depletion in virgin mines. However, applying circularity indicators to C, N and K will highlight other issues. Therefore, it is important to bear in mind that P is not representative for the other macronutrients.

5.1.1 POC_{index}

By applying the POC_{index} method, all four regions resulted as class C, which was earlier defined as regions where mixed sourced material prevail, no reuse practices dominate, and organic waste is predominantly used for landscape or either landfilled. Additionally, regions with POC_{index} values that range between 25-50, have incineration as predominant energy recovery strategy (Table 5).

Brandenburg presents around 44% of P that is incinerated (Sludge, flow nr. 23) and 13% of P in form of biowaste that is incinerated (flow nr. 22). These two flows make up more than half (57%) of P waste management for Brandenburg and have a great impact on the overall result of the POC_{index} (value 34).

On the other hand, Denmark for example, directs 70% of P-waste in form of sludge for farm application (flow nr. 16) and 23,9% as compost applied for landscaping (flow nr. 17). Since these two flows generate more points according to the CNE objectives in contrast to flows nr. 22 & nr. 23 of Brandenburg, the POC_{index} value of 49 Denmark, is the highest of all four regions.

Switzerland and Brussel capital are interesting to discuss since they both have a similar POC_{index} value (27,6 and 28,4). The two regions mainly direct organic waste via incineration, 58% and 60,1% of total P, respectively. Furthermore, Switzerland disposes 23,2 % of total P in form of sludge to construction (flow nr. 27), which is according to the herein definition, the worse path with the lower CNE benefits (*k*-value = 0,12; Table 7). The second largest flow of Brussel capital, on the other hand, is collection of organic biowaste for heat recovery (16,9% of total P), which has a higher k-value (0,38).

By considering only the two largest flowss, Brussel should gain a higher POC_{index} score in contrast to Switzerland, nevertheless, since Switzerland has a higher percentage of P-recovery in form of digestate to farm (5,2% vs. 0,2% for Brussel) and a higher compost application on farms (5,2% vs. 0,5%), which are two flows with rather high *k*-values (0,72 & 0,52), this evaluation method allows to consider the positive benefits and results therefore in a higher POC_{index} value for Switzerland, even if the second largest flow in this region is sludge application in the cement industry.

5.1.2 POC_{index} effectiveness

With the integration of a hierarchy analysis framework for regional CNE, the POC_{index} gives a better framing for recycling of organic matter, depending on its end benefits and application purposes.

According to the definition of circular economy by Kirchherr et al. (2017), the ranking order of the R-framework should be somehow included in circularity assessment. One reason for this is that otherwise CE practitioners' risk to prioritise recycling over reduction strategies, leading to the risk of perpetuating business-as-usual economies (Kirchherr et al., 2017). Besides, it has been emphasised that in the context of CE-indicators, little attention is paid to the qualitative aspects of nutrient cycles (Moraga et al., 2019). Therefore, a hierarchized assessment of the flows (such as ranking composted vs. incinerated biomass) is missing in current CIs and the POC_{index} can be seen as a useful tool to overcome this limitation.

In the case of Brandenburg twenty flows have been identified, leading to a higher resolution. Therefore, the final POC_{index} score is better tuned between negative contributions (flows nr. 24, 25, 26, and 27) and positive contributions (flows nr. 4, 5, 6, 7, 9, 10, 12, 13, 15, and 16) that "balance" each other out (Figure 4). This is not the case in the other regions, where for Denmark only four flows have been found and only six for Switzerland and seven for Brussel.

The fact that the four regions have been analysed by using a different number of flows might negatively influence the benchmark analysis between regions, and for future studies it would be therefore advised to find the same number of flows for every region when comparing them to evaluate their CNE performances.

5.1.3 POC_{index} versus Circularity

In contrast to POC_{index}, by applying C as an indicator of circularity, Switzerland appears to be the best performing region with a score of 50,1, followed by Brandenburg (44,5), Denmark (28,7), and Brussel (1,4) (Figure 5, A).

Switzerland and Brandenburg present large manure flows of 23,353 t P a^{-1} and 9,146 t P a^{-1}, which correspond to 42,7% and 24,7% of the total system throughput, respectively (Table 9). In these two regions, manure as a recirculated mass gives an important contribution for the C final score, which explains why Switzerland and Brandenburg are better positioned in comparison to Denmark, which on the other hand has a higher POC_{index} value (Figure 5, A).

Brussel capital region does not score well in Circularity (C=1,4) because the total mass of Recirculated Mass is very little compared to the total System throughput. This is because in the Brussel study case, no farmland is included as subsystem and therefore the urban capacity to recycle organic waste is yet limited. This recalls the differences in scores of Circularities emphasized by Papangelou et al. (2020) about the three options of applying the indicators City Circularity (CC), Food Circularity (FC) and Weak Circularity (WC).

Tanzer et al.'s (2020) circularity indicator assigns the same qualitative weight to manure recovery as it does to recycling in cement plants. However, the POC_{index} introduces a compelling extension by weighting material flows based on their final CNE benefits. This approach is particularly valuable in the context of organic waste management, as it shifts the perspective on recycling: rather than focusing solely on material recycling, it emphasizes the efficiency of cascading processes and the broader benefits they deliver.

Lastly, Switzerland's high C score of 50,1 in contrast to the rather low POC_{index} score of 27,6, also shows that even if Switzerland is performing well in recycling, by recovering mainly P as *sludge to heat* (flow nr. 23), the C indicator is limited in showing the recycling benefits only, while the POC_{index} weights the flows in the calculation method from a hierarchical CNE perspective, and gives an additional qualitative evaluation. Which means that even if Switzerland recycles 1:2 of P in its System, its final CNE benefits are of class C, which gives additional valuable information in respect to CNE objectives.

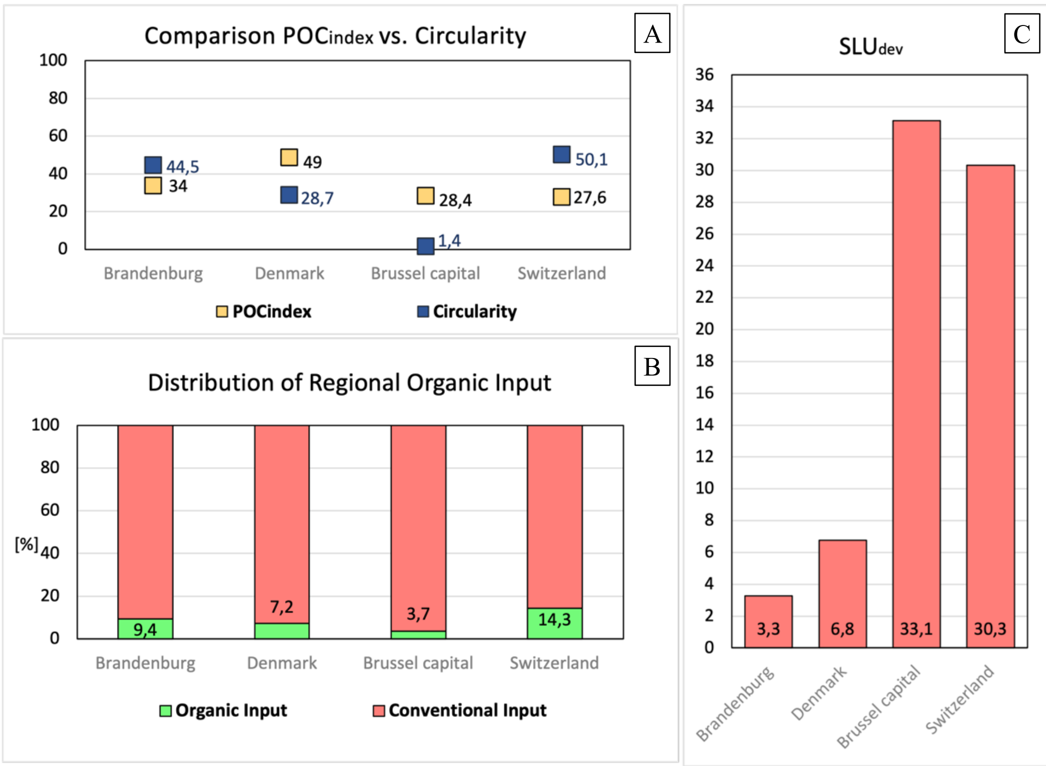

Figure 5. In Figure A, the POC_{index} is presented alongside circularity C (Tanzer et al., 2020) for all four regions under study. Figure B illustrates the percentage share of organic input relative to conventional input across the same regions. Lastly, Figure C displays the SLU_{dev} values, which have been calculated for each of the four regions.

5.1.4 POC_{index} hypothetical improvement scenarios

If Brandenburg were to redirect its conventional biowaste (nr. 22) to BSF upcycling for feed production, for example, and recover all the phosphorus (P) from the sludge in the form of struvite (nr. 4) instead of incinerating it (nr. 23), its POC_{index} score would increase from 34 to 58, raising its class from C to B.

On the other hand, if Denmark were to make the effort to raise its score from C to class A, it would be necessary to ensure that only products sourced from organic materials are used throughout the production and consumption subsystems. Additionally, all sludge (nr. 16) should be recovered in biogas plants (nr. 1) and subsequently applied to fields, while all conventional compost used for landscaping (nr. 17) should be fed to BSF for feed production (nr. 3). If these measures were taken, Denmark would achieve a POC_{index} score of 75. If it were to additionally reduce the outflow from the WWTP to zero, its score would rise slightly to a POC_{index} of 79.

If Brussels were to redirect its biowaste from incineration (nr. 21) to BSF production (nr. 3) and increase its recovery of sludge in the form of conventional digestate for use on farms (nr. 5) by eliminating sludge incineration (nr. 23), this would result in a POC_{index} of 60,3, upgrading from class C to class B.

As sludge application on farmland is not permitted in Switzerland, this is not a feasible option. Therefore, it is also not possible for the region to achieve a B or A classification. However, it would be possible to divert the sludge from incineration (nr. 23) and construction (nr. 27) to flow nr. 19 (AD WWTP energy recovery + heat production). This would mean installing biogas plants on all WWTP to recover additional biogas, alongside heat from incineration. Nevertheless, these measures would not significantly improve the CNE score for Switzerland, only increasing the POC_{index} from 27,6 to 33,9 and maintaining a low score categorised as class C.

5.1.5 SLU_{dev}

As all regions have a SLU_{dev} >1, meaning that the marginal land used as feedstock is exceeding the potential land capacity (Figure 5, C).

Brandenburg and Denmark seem to be lesser intensive, by having a SLU_{dev} ranging between 3 and 7 units and are therefore relying more on local grassland available from regional marginal land. Brussel capital and Switzerland instead need 30 times more grassland-feed resources than locally available, which makes these two regions less independent and sustainable, since they need to use way more outsourced feed than Brandenburg and Denmark (Figure 5, C).

In opposition to the Feed-self Sufficiency (FSS) indicator used by Koppelmäki, et al. (2021) (Table 2), which is based on masses of production and import per hectare, the SLU_{dev} gives a more specific insight since it includes the marginal land availability for each region, excluding cropland and fertile agricultural areas.

However, the calculation method for the SLU_{dev} is built on data that considers literature-based averages, which do not reflect each region characteristics specifically. As for example the estimation of Qi et al. (2023) concerning DM grassland consumption of ruminants. And also the estimation of the soil quality of Gerwin et al. (2018) used in this method for Denmark, Brussel and Switzerland, is a weak estimation of available marginal land since it was for all regions 10% of total cropland. In contrast the method that was applied on Brandenburg is more reliable as it comes from a study that estimated the soil fertility using the M-SQR (Tavakoli-Hashjini et al., 2020).

5.1.6 Share of organic P Input

Regarding the share of organic P input, the main interesting aspect to note is that up to date the four studied European regions rely on around 10% of organic inputs across import, production, and retail market sectors (Figure 5, B).

For all regions ± 90% of the biomass inputs can be considered of conventional nature, which arises the hypotheses that consumption of goods in Europe are potentially contaminated by unseen toxicants derived from pesticides and mineral fertilizers. But these are speculative conclusions, and the share of organic P input isn't a performant indicator, because it only shows that organic farming is rather unpopular and not well established at the European level. The regional assessment of toxicity and regenerative benefits of materials should be measured in other ways.

However, even if organic farming is granted as more sustainable and circular, it is still challenging to achieve equal fertilisation performances compared to mineral fertilizers. In fact, P-availability in organic sources is highly influenced by processing and storage practices of compost and manure (Vanden Nest et al., 2021).

Further factors such as pH and Ca/P ratios in the products also influence plant P-availability, determining if the organic fertilisers contain predominantly the highly soluble form (struvite) or insoluble mineral apatite, which inhibits plant availability (Vanden Nest et al., 2021).

From a soil regenerative perspective, the time scale of soil formation is off the human time scale and therefore not a factor that generates economic value in the short term.

However, soil is the most valuable natural resource in the long term, but even if the use of recycled organic fertilizer will restore local soil health (Obalum et al., 2017) and be a more circular system, the use of organic sources will not completely alleviate environmental, water, and soil conservation pressures. This is because soil degradation is the result of intensive agricultural activity, which leads to problems of soil compaction, reduced soil formation and erosion, which are primarily caused by poor management practices (Seeger Manuel, 2023).

5.2 Further conceptual gaps

As mentioned in the Methods section, *Input Circularity* (Harder et al., 2021) was not taken into consideration in the proposed framework, since it would have been way more work. This means that unfortunately, P flows from mined sources, imported goods and feed, and environmental inputs have not been assessed. However, to have a complete picture of the system P flow dynamics, these flows need to be considered as well. The substance concentration efficiency (SCE) indicator proposed by Tanzer et al. (2020), which is well suited to reducing material inputs, could be therefore recommended for application.

In this study and in the literature, no clear methodology for determining the "linearity" of a regional bioeconomy has been found. Also, the EMF does not discuss how to calculate the Linear Flow Index (LFI) of biological materials in their methodology section concerning circularity (Goddin et al., 2019). This is a relevant gap, as no indicator has been identified to assess the linearity of a region, with perhaps only the concept of system openness being the closest attempt to assess system linearity to date (Harder et al., 2021).

5.2.1 System openness

From the summary of Table 2 and the outcome of the applied indicators, it has been shown that measuring circularity is highly context specific and the type of nutrient unbalances define the indicators: intensive agricultural practices generate high environmental losses, have a high resource consumption and are dependent on global trade (Van Der Wiel et al., 2021). Extensive agricultural practices on the other hand, show the opposite trend, with the one negative aspect of low nutrient efficiency and therefore low productivity (Le Noë et al., 2017).

The POC_{index}, the SLU_{dev} and the share of organic P input are not considering the influence of flows outside the SB. As Harder et al. (2021) discusses with his concept of system openness, CNE is complex to restore because of a globalised distribution of the accumulation of nutrients in areas of consumption (cities) and the depletion of nutrients in areas of production (farms).

Nevertheless, Van Der Wiel et al. (2019) identifies the regional or local scale unit as the most important starting point to address nutrient management, in which the subsystems of the agro-food-waste system are close enough to create an economically feasible exchange network. On a subnational level, circularity and tight food supply distances are acknowledged as key factors for a sustainable food system (Kaufmann et al., 2022).

Considering that not every region can recycle nutrients on agricultural land because of either excess manure or sewage production in combination with a small agricultural area, these kinds of regions would be more responsible in valorising nutrients by exporting them for reuse, rather than incinerating or landfilling. In a region with excess manure production and application, circularity indicator based on MFA are likely to have huge losses from the soils and nutrient flows in waterbodies, as there is no regional capacity to recycle nutrients. In such a context, in addition to the circularity performance it would be interesting to evaluate for example the potential to export nutrients to neighbouring regions (Hanserud et al., 2017).

5.2.2 Renewable Energy and Nitrogen

With respect to energy consumption, which is expected to increase due to population growth and an increase in CE approaches, it will be challenging to address energy consumption in the context of CE. In fact, some authors argue that a system can be considered circular if industrial N_2 fixation is produced by renewable energy sources (De Boer & Van Ittersum, 2018).

There is a lack of clear definition of material scarcity and sustainability specifically for Nitrogen. In fact, from a CNE perspective, the atmospheric N stock cannot be easily defined as virgin as P coming from rock mines because of its unlimited availability in the atmosphere, and the fact that it is not considered as a critical resource as P, requires a new CNE conceptualization specifically for N.

Other findings that reenforces the idea of applying different assessment methods between N and P is emphasized by the study on nutrient circularity of Cobo et al. (2018). The study shows that N-leaching increases with the application of organic fertilisers, but not for P which is predominantly bound to soil particles (Cobo et al., 2018). From an environmental impact perspective, their results suggest that increasing the use of organic fertilisers to address circularity might lead to an increase in N eutrophication but are not affecting P eutrophication (Cobo et al., 2018).

5.2.3 Social, natural, and economic factors

In many studies the use of the indicator self-sufficiency between urban areas and the supplying rural areas is used, this expresses a region's reliance on net imports and is the ratio of domestic agricultural production to consumption (Kaufmann et al., 2022). From a biophysical perspective, while it would be the most sustainable option for any country to be self-sufficient, in many countries this is not possible due to either agricultural land, water, or a combination of both constrains (Fader et al., 2013).

Fader et al. (2013) estimated that in North Africa and the Arabian Peninsula, for example, even if agricultural efficiency were increased, the natural limits (renewable water and land availability) would not allow food self-sufficiency.

Even if SLU_{dev} can be seen as a useful tool to distinguish cropland from grassland resources, there are regions where cropland is scarce, if not present at all. According to Adesogan et al. (2020), Animal Sourced Food (ASF) plays a key role in providing nutrient-rich animal foods to low- and middle-income countries that are exposed to chronic malnutrition, particularly in the sub-Saharan regions that rely on arid climate and large areas of grasslands that are not suitable for crop cultivation (Adesogan et al., 2020). These countries additionally rely on food imports because there is not enough fertile soil for crop production.

On the other hand, natural constraints are not an issue in other regions, such as South America, where the factors influencing import dependence are more related to a lack of capital, know-how, and labour (Fader et al., 2013).

In the contrast, the import dependency in more developed regions of Europe, such as the Scandinavian countries, is of political nature. Even though fertile soils would be available, these countries have been focusing on the development of other economic sectors or enhanced the protection of natural ecosystems. From a bioregional perspective, in these countries the soil fertility would allow self-sufficiency and provide goods to be exported to other countries too (Fader et al., 2013).

5.2.4 CNE as a global challenge

Many strategies have been proposed to achieve global and sustainable food security. Among the many solutions discussed there are also considerations of redistributing crops within cultivated lands to reduce water stress (Davis et al., 2017), increasing production through sustainable intensification of agriculture (Godfray & Garnett, 2014), changing diets towards plant-based protein consumption (Poore & Nemecek, 2018), or combination of measures that would lead to the adoption of circularity principles in food systems (Van Zanten et al., 2023).

The caloric content of global food production is estimated to be sufficient to feed the world demand, and even if 25% of commodities are currently traded internationally, there are still countries facing chronic food scarcity and are unable to meet local demand due to agroclimatic constraints (D'Odorico et al., 2014).

This means that regional efforts to become more circular should consider the global context, since regions with limited production due to natural or political constraints will further depend on imports, and there is no guarantee that the development of technologies that can compensate for these food gaps will be sufficient to achieve global self-sufficiency for every region. In addition to natural variables, Muscat et al. (2020) argue that the integration of economic factors (labour and capital) is also necessary and will greatly affect the provision of increasing biomass demand. Even if regional system analysis is complex to assess, social, natural, and economic variables need to be measured in a complementary way. From a scientific perspective it is therefore necessary to develop further indicators that address CNE objectives but also consider the global food security and environmental degradation issues that humanity is facing across the entire globe.

6. Conclusion

Circular Nutrient Economy (CNE) is built on CE principles focusing on nutrient flows, and strategies (reducing, narrowing, closing, slowing, and regenerating) with the scope of achieving a more efficient nutrient use. In addition, biological cycles in the context of CNE consider the sustainability of sourcing materials and the cascading performance (up- and downcycle). The fact that CNE definitions are not yet clearly defined, poses great challenges when trying to assess its performance by using indicators.

This thesis focuses on *Output Circularity*, considering only the system outflows and recirculation. The analytical framework proposed herein allows us to deduce the following three important criteria that must be addressed when developing CIs at the regional level: a stricter application of the 4R framework, clarification of the bioregion and its biomass production limits, and stricter assessment of safety and regeneration.

A novel analytical framework, the so-called hierarchy analysis framework for regional CNE, has been proposed to develop CIs. The proposed theoretical conceptualization wants to primarily address the concepts of prioritizing food over feed and feed over bioenergy production, enable nutrient efficient coupled crop-livestock practices, and lastly address the less emphasized objectives of CNE so far: regeneration and safety of materials.

The Ellen MacArthur Foundation (EMF), start-up companies that produce compost from dry toilet, or environmental institutions could use the indicators developed here to evaluate the level of circularity in their regions. These indicators are particularly useful for assessing biological material integrity, the adoption of the 4R framework, safety issues, and regeneration. Furthermore, this set of indicators is of particular interest to CNE promoters because sustainable treatment practices are often evaluated using traditional environmental or economic indicators. And these indicators do not encourage decision-makers due to high biogenic CO_2 emissions, the higher risks of eutrophication and the high cost of adapting infrastructure for new nutrient management systems.

For future work, if the analytical framework for CNE is to be improved, it will be important to also integrate further aspects of GHGs emissions, Input Circularity, and system openness (global trade). Furthermore, a contextual biophysical and demographic regional analysis can also provide the base to know what “type” of circularity must be addressed, since there are regions that face different problems depending on their nutrient imbalances (net importers vs. net exporters).

6.1 POC_{index}, SLU_{dev}, and the Share of organic P input

The application on four European regions showed that the quality of Circularity, following Tanzer et al.'s (2020) conceptualization, in Brandenburg, Denmark, Brussel capital, and Switzerland is still of lower quality (class C). However, the most intriguing finding of this study is that, although Denmark recovers less in terms of P-quantities than Switzerland and Brandenburg (Circularity = 28,7 compared to C = 50,1 and C = 44,5, respectively), the POC_{index} reveals that Denmark, despite being less efficient, aligns more closely with CNE principles. This is reflected in Denmark's relatively high POC_{index} of 49, compared to Switzerland's 27,6 and Brandenburg's 34. This method can be easily applied on other already existing regional P-MFAs studies.

However, because of the very low score of Brussel capital, this study shows that the application of the POC_{index} functions only on P-MFAs that present data for all five major subsystems (crop production, livestock production, food and feed processing, consumption, waste management).

SLU_{dev} and organic P input aimed to assess livestock-marginal land connectivity and regional potential contamination level. However, these two methods clearly lack scientific and mathematical rigor, requiring further refinement. Nevertheless, the SLU_{dev} shows, all regions exceed marginal land capacity for feedstock production, with Brandenburg (SLU_{dev} = 3,3) and Denmark (SLU_{dev} = 6,8) being relatively more self-sufficient than Brussel capital (SLU_{dev} = 33,1) and Switzerland (SLU_{dev} = 30,3). While this method offers a more detailed assessment considering the marginal land soil capacity, its reliance on literature-based averages limits its accuracy.

Regarding the regenerative and safety assessment, organic P inputs remain low in Europe, with conventional sources dominating and raising potential contamination concerns. Even if organic farming is argued to be more secure (Gabriel et al., 2010), this study recognizes that a broader assessment method is needed to evaluate safety and toxicity more effectively.

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Popular science summary

Biological resources are essential for humans. On the other hand, organic waste like sludge from wastewater treatment plants, or food waste, can be upcycled into new products or used as fertiliser, which is ultimately also beneficial for soils to build up humus and regenerate. The idea of a Circular Nutrient Economy (CNE) is gaining attention as the world seeks to reduce organic waste and make better use of biological resources. Instead of following a "linear system", where materials are either misused (energy made with edible crops or nutrients lost in emissions) or used once and landfilled, CNE focuses on prioritizing the use of resources and reusing nutrients as much as possible to minimize environmental harm and reduce dependence on imports.

Researchers have explored different ways to measure how well regions are adopting CNE principles, but there's no universal agreement on the best approach. This study reviews existing methods and proposes a new framework to assess nutrient circularity in different regions. To test this method, this study applies the new developed framework and method to four locations in Europe: Brandenburg (Germany), Denmark, Brussels-Capital, and Switzerland.

This study identifies three criteria that need to be acknowledged in regional circular nutrient economies, including reducing nutrient losses, which also aims at reducing eutrophication (nutrient-driven pollution of waterbodies and land), reusing materials, ensuring safety of consumption goods, using biological resources in respect to the local context, and relying more on renewable energy.

To measure progress towards these listed goals, this study developed the Phosphorus Output Circularity Index (POC_{index}), which grades how well a region retains and reuses phosphorus, an essential nutrient for agriculture. This method works like ABCD-rating labels which already exist, for example labels used to rate the nutrition degree of food products. Unfortunately, all four regions received a C score, indicating room for significant improvement (A represents the highest class with more regional benefits from a CNE perspective).

Organic farms produce pesticide-free goods and only use manure or compost as fertilizer. One major issue highlighted in this study is that only about 10% of food products in the studied regions come from organic farming, which raises concerns about safety of derived organic waste potentially reusable at the European level. Furthermore, this study used an indicator (SLU_{dev}) to better understand the limit of livestock production fed with local marginal land (soils that cannot be used for crop production). It was shown that all regions still rely heavily on imported animal feed, making them vulnerable to supply disruptions and not in line with CNE goals.

In conclusion, this study acknowledges limitations in current definitions of CNE and the herein developed indicators. Nevertheless, research and policymakers need standardized ways to measure nutrient circularity. In this way relevant decision makers will be able to apply indicators to tackle a more sustainable, efficient, and circular approach to managing nutrients at regional and global levels.

Appendix 1

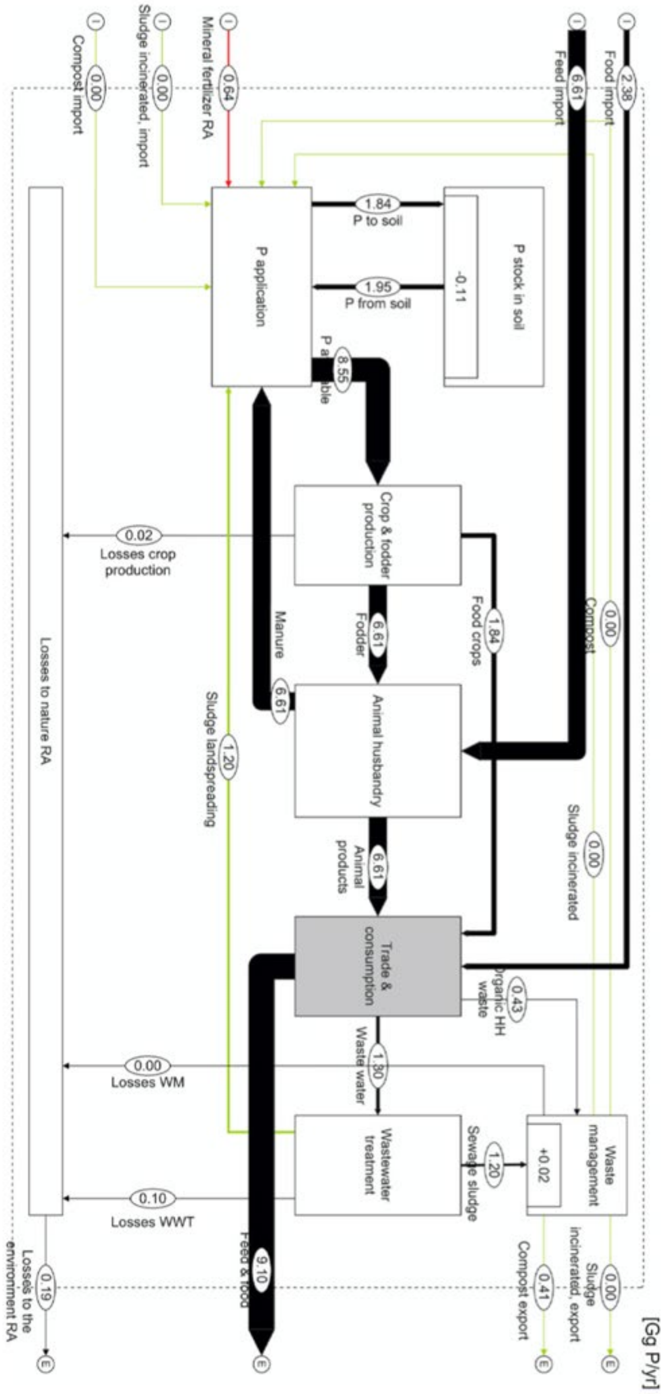

Figure 6. MFA system of the Danish P household (in Gg P/year) in region A (original MFA from the study of M. Klinglmair et al. (2017))

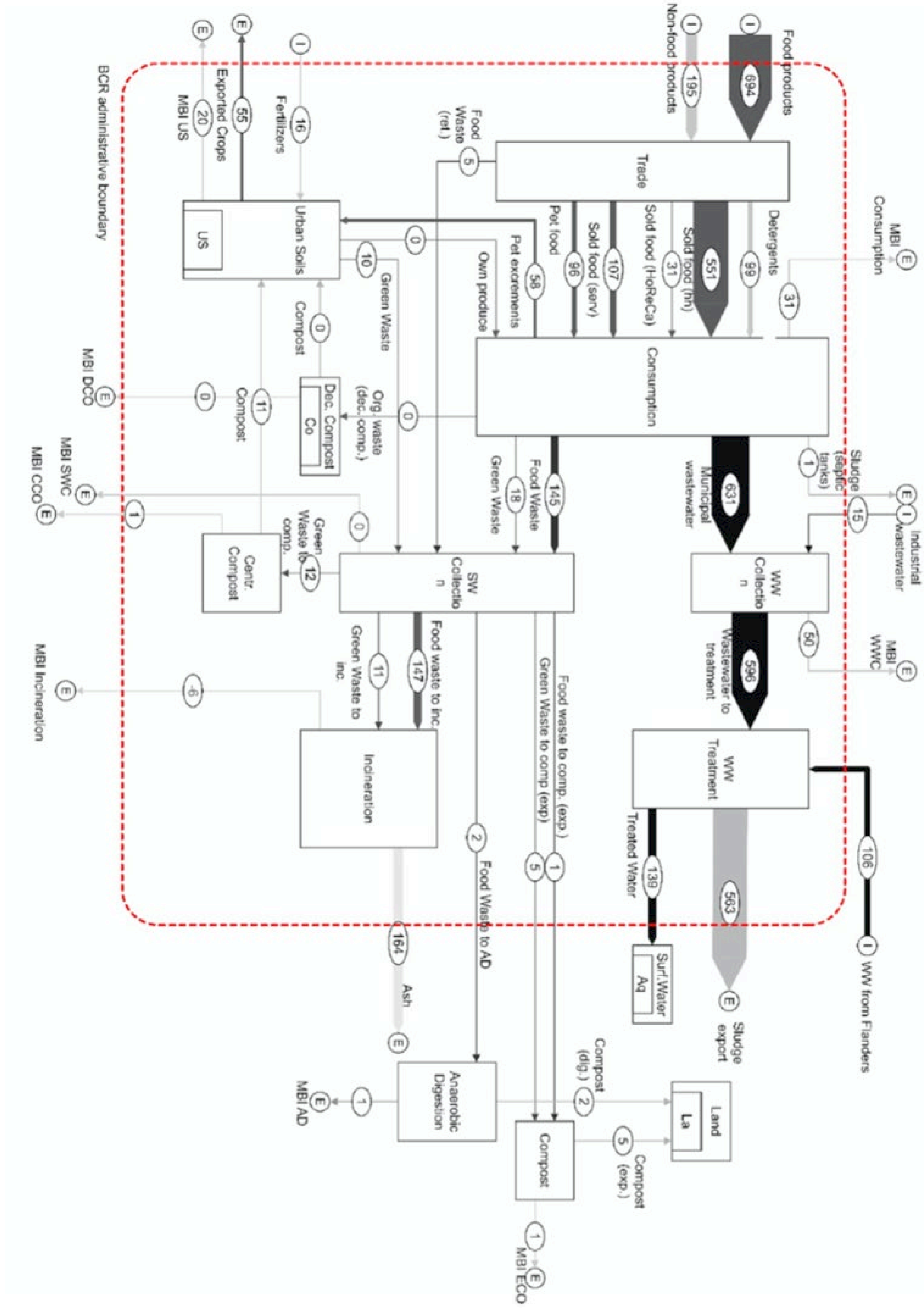

Figure 7. MFA system of the Brussel capital P household in tonnes P/year (original MFA from the study of A. Papangelou et al. (2020))

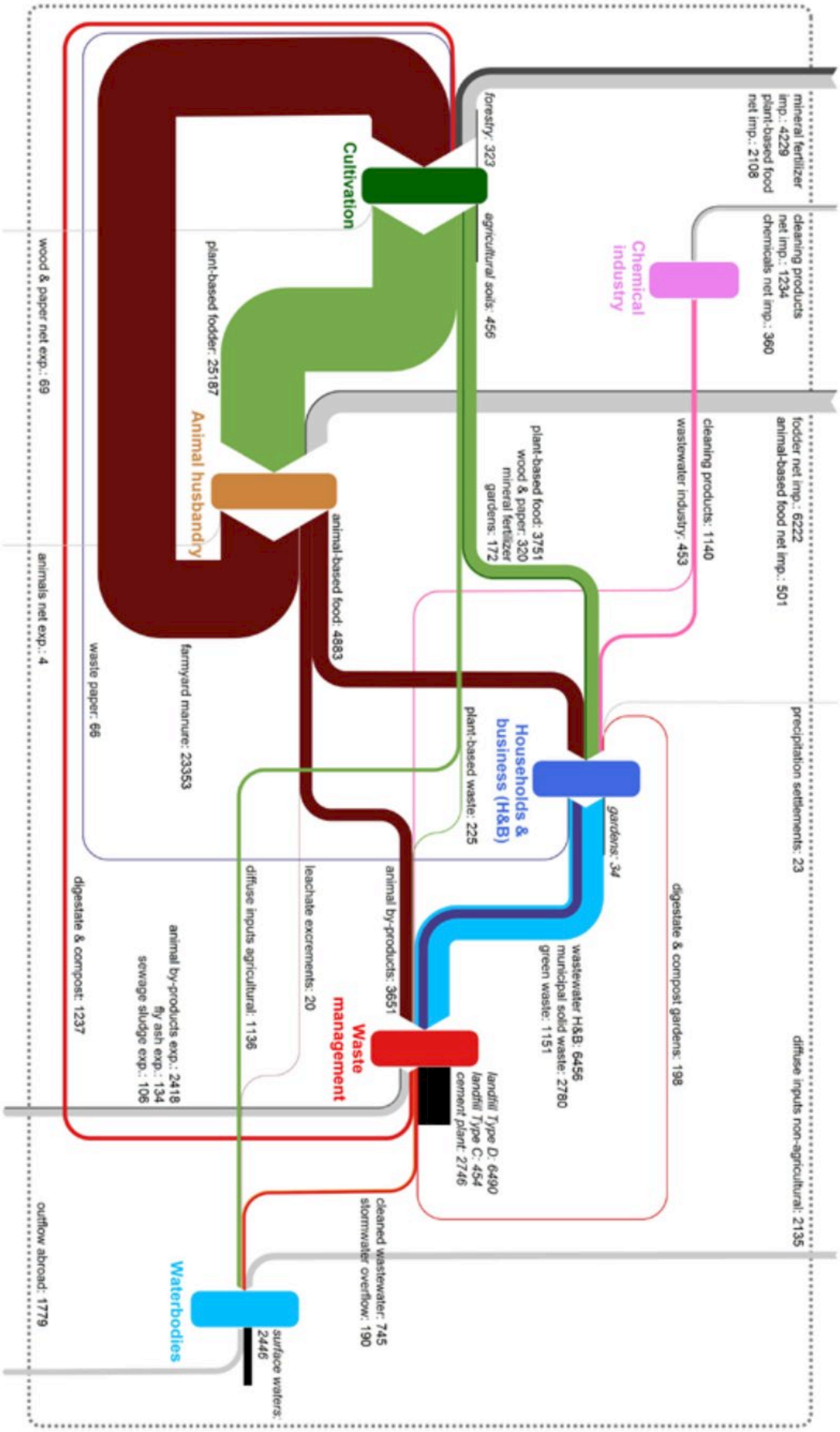

Figure 8. MFA system of the Swiss household in tonnes P/year (original MFA from the study of Mehr et al. (2018))

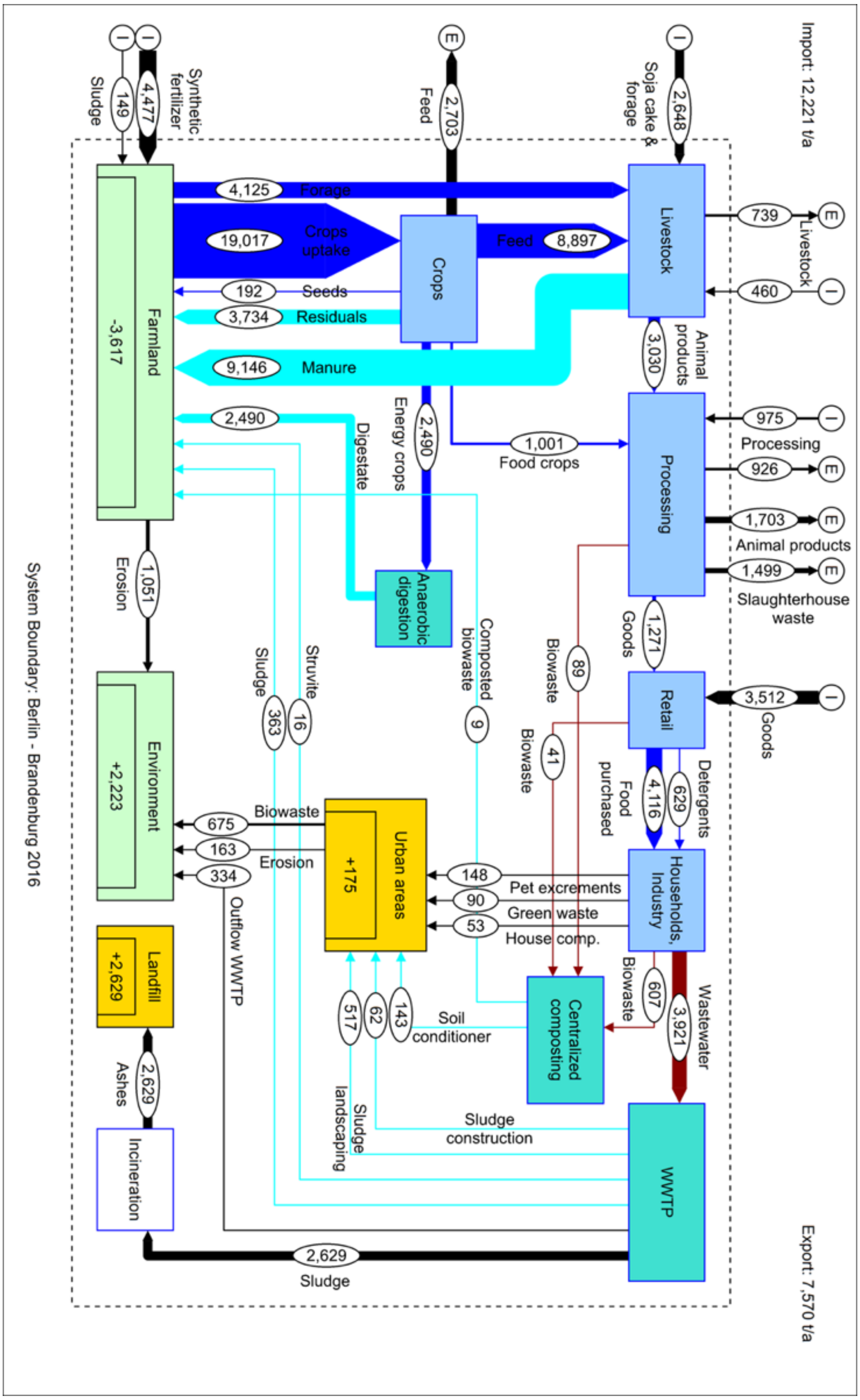

Figure 9.P flows in tP a^{-1} from the study by Theobald et al. (2016). In case of non-compliant or missing data other sources have been used and adjusted to the unit (e.g., soja cake and forage import (Data (FAO, 2021); P content (NRC, 2005) & (Tampio, et al., 2015). The graphical representation of the masses for Brandenburg region was facilitated by the latest version of the software STAN (version 2.7.101) available under: www.stan2web.net.

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