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Situating the discourse of recycled nutrient fertilizers in circular economy principles for sustainable agriculture

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This mini review explores the integration of recycled nutrient fertilizers (RNFs) into practices for sustainable agriculture within the circular economy framework. Regional nutrient imbalances challenge the efficiency of implementing nutrient recycling and concerns about contaminants such as potentially toxic elements, microplastics, and antibiotic resistance genes hinder the adoption of RNFs. This review examines the technological, environmental, economic, and policy dimensions of nutrient recycling, highlighting how these practices align with circular economy principles to promote resource efficiency, waste reduction and reduced environmental impact. The review underscores the importance of economic feasibility, supportive policies, and public perception in facilitating RNF adoption. Technological innovations like struvite precipitation and biochar production show promise but face challenges such as high costs and contamination risks. Effective policy frameworks and stakeholder engagement are crucial for broader acceptance. This interdisciplinary review draws insights from environmental science, economics, and agricultural engineering, contributing to a comprehensive understanding of how RNFs can enhance sustainable agricultural practices. The findings suggest that continued technological innovation, effective contamination management, supportive policies, and market incentives, combined with stakeholder education on the benefits and safety of RNFs, can significantly improve public perception and adoption. Together, these factors can contribute substantially to building a more sustainable and resilient agricultural system.

KEYWORDS

circular economy, nutrient recycling, biobased fertilizers, new business models, agriculture technology and innovation

1 Introduction

The transition to sustainable agriculture has sparked growing interest in the use of recycled nutrient fertilizers (RNFs), which are generally derived from organic biomass streams such as manure, wastewater sludge and industrial food waste. These types of fertilizers offer the potential to close nutrient loops and contribute to a circular economy by returning essential nutrients like nitrogen (N) and phosphorus (P) back to agricultural soils. The production and use of RNFs provide an opportunity to reduce dependence on synthetic fertilizers which would mitigate greenhouse gas emissions associated with the production of synthetic fertilizers, while also reducing the environmental burden associated with treatment and disposal of these nutrient rich waste streams (van der Wiel et al., 2023; Callesen et al., 2022). However, the implementation of RNFs raises several key challenges that must be addressed to ensure their successful integration into sustainable agricultural practices.

One of the primary issues is the variability in the nutrient content of RNFs, which is influenced by the source and treatment process of the biological waste stream (RISE, 2016; Chojnacka et al., 2020). The variability complicates standardization efforts, making it difficult for farmers to apply precise nutrient amounts tailored to crop requirements. Furthermore, the nutrient release patterns of RNFs can be less predictable than those of synthetic fertilizers, as nutrients are often present in organic or less bioavailable forms (Firmanda et al., 2024; Mikula et al., 2020). This unpredictability can impact crop yields if not managed correctly. Additionally, the potential for ammonia volatilization, particularly in manure-based RNFs, can diminish the environmental benefits of these fertilizers by contributing to air pollution and N loss (Kurniawati et al., 2023). Concerns about contaminants, such as potentially toxic elements, microplastics, and antibiotic resistance genes, create doubts among organic farmers regarding the safety and health impacts on soil and crops. Although some contaminants are declining, and soils show resilience in degrading or stabilizing pollutants, uncertainties persist. The integration of nutrient recycling within the broader circular economy framework aligns with organic farming principles, promoting the reuse of societal waste streams to reduce reliance on finite mineral resources and minimize environmental impacts (Aarikka-Stenroos et al., 2023). Addressing stakeholders' concerns about health risks, environmental pollution, and technical reliability is essential for broader acceptance of RNF (Aarikka-Stenroos et al., 2023; Schmidt and Eyeem, 2020).

Economic factors also play a significant role in the adoption of RNFs. Small-scale processing, production, and distribution of these fertilizers will usually be costlier than conventional synthetic fertilizers produced at industrial scales with heavy reliance on cheap fossil fuels. Furthermore, the availability of RNFs is often limited to regions with appropriate organic waste streams (Akram et al., 2019). Farmer acceptance of RNFs is hindered by the perception that they are less reliable than synthetic fertilizers which are widely used due to their reliable nutrient content, ease of application and predicable crop response. Overcoming these barriers will require not only economic incentives, but also a concerted effort to build trust in RNF efficiency as well as the added value of their use.

Regulatory frameworks play a pivotal role in facilitating the broader adoption of recycled nutrient fertilizers (RNFs). Establishing consistent certification standards for nutrient content, contaminant levels, and overall fertilizer quality and efficiency is crucial for developing a viable market for RNFs, ensuring their safe and effective utilization (Kurniawati et al., 2023). Current regulatory policies tend to favor synthetic fertilizers. A strategic shift in these policies is vital to address the technical and economic challenges associated with RNFs and to foster their integration into sustainable agricultural systems. While the long-term use of RNFs can enhance soil structure and increase organic matter content, it is important to note that without proper management, their application could lead to nutrient imbalances, increased runoff, and environmental contamination, posing risks to both environmental health and soil integrity.

Technological advancements in waste processing and agricultural management offer promising solutions to many of these challenges. Innovations such as anaerobic digestion, pyrolysis, and precision agriculture tools can enhance the efficiency and nutrient recovery potential of RNFs. However, adequate infrastructure for the collection, treatment and distribution of organic waste is crucial to making these technologies accessible on a larger scale (Akram et al., 2019). Finally, public perception and education remain pivotal in the broader acceptance of RNFs. Many farmers and consumers remain skeptical about the safety and efficacy of fertilizers derived from waste, particular human waste or sludge. Raising awareness about the benefits and safety of RNFs, along with providing training and technical support for their effective use, will be key to promoting their adoption (Reimer et al., 2020).

In summary, the discourse on the role of RNFs in sustainable agriculture encompasses a complex array of environmental, economic, regulatory and social issues. Public perception plays a critical role, as addressing local concerns can enhance the legitimacy of implementing new processing technologies (Callesen et al., 2022; Reimer et al., 2020). This paper aims to explore these challenges through a mini-review to place the current discourse and concerns regarding nutrient recycling and RNFs within the broader context of the circular economy, aiming to investigate how the role of RNFs can be integrated into sustainable nutrient management and best agricultural practices to encourage widespread uptake and use of RNFs.

2 Unpacking the research landscape

A meticulous literature search was conducted across 626 databases (University of Gothenburg library databases), which include well-regarded sources such as CINAHL, PubMed, and Scopus. This initial search yielded 16,125 publications pertinent to the keyword *nutrient recycling*. The retrieved list that contained the relevant keywords was then refined based on criteria requiring availability of the "full text," designation as "scientific articles," and "open access" status, resulting in 6,124 articles. This substantial volume of literature highlights the growing scholarly focus on nutrient recycling, underscoring its significance in promoting sustainable agricultural practices. From this smaller collection of articles, 9 journal articles (van der Wiel et al., 2023; Callesen et al., 2022; Chojnacka et al., 2020; Akram et al., 2019; Bünemann et al., 2024; Duboc et al., 2022; Egas et al., 2023; Goulding et al., 2008; Zhang et al., 2020) were meticulously selected for detailed review. The criteria for selection included:

1. Open Access: Ensuring the articles are freely available to maximize accessibility and dissemination of knowledge.
2. English Language: To cater to a broad academic audience and ensure ease of integration into global discourse.
3. Review Nature: Preference was given to review articles to provide synthesized perspectives and insights into the field of nutrient recycling. Specifically, articles by Bünemann et al. (2024), Egas et al. (2023), and Zhang et al. (2020) were chosen for their comprehensive reviews of various aspects of nutrient recycling.
4. Methodological Diversity: Articles were selected to represent a diverse array of research methodologies and focuses, including technological, environmental, economic, and policy dimensions of nutrient recycling. This diversity ensures a holistic understanding of the field and its various applications within the circular economy.

By analyzing these articles, illustrated in Tables 1, 2 this review delves into the diverse technological, environmental, economic, and policy-related dimensions of nutrient recycling. It underscores how nutrient recycling practices can become integral to the circular economy, facilitating sustainable development in agriculture. This approach not only enriches the review's narrative but also provides a robust foundation for advocating advanced recycling technologies and policies.

3 Analysis of terminological trends and historical context

The online open access search tool, Google Books Ngram Viewer, was used to trace the usage of the term "recycled nutrients" over a period of 100 years, from 1900 to the 2020s, revealing insightful trends about its incorporation into academic and practical discourse:

- Pre-1960s Observations: The virtual absence of the term prior to the 1960s suggests it was not yet a recognized concept within mainstream scientific or agricultural discussions, or it may have been described using alternative terminology.
- Increase from 1960 to 1990: The noticeable increase in the usage of "recycled nutrients" during this period aligns with a rising consciousness about environmental sustainability and the onset of sustainability as a crucial scientific and societal issue.
- Peaks in the 1990s and 2000: These peaks are likely indicative of concentrated research efforts and the implementation of related policies, driven by growing environmental concerns and innovations in recycling technologies.
- Post-2000 Trends: The subsequent decline and eventual stabilization in the usage of this term may reflect a maturation within the field or the adoption of new terminologies that more accurately reflect evolving technologies and methodologies.

4 The discourse of recycled nutrient fertilizers: selected studies

The literature mini-review set highlights several trends and common findings. It begins with *(i) technological innovations and challenges*, providing a basis for discussing *(ii) methodological rigor and interdisciplinary approaches* that drive advancements in this field. The narrative then explores *(iii) environmental and economic implications*, pivotal in understanding the broader impacts of nutrient recycling. This leads into *(iv) contaminants and safety concerns*, a crucial aspect of any sustainable technology and practice. Following this, *(v) policy and regulatory frameworks* are examined, which are influenced by technological capabilities and environmental considerations. The discourse then moves into *(vi) farmer acceptance and public perception*, reflecting the societal aspects of technology adoption. Finally, it concludes with *(vii) spatial and logistical considerations*, which encapsulates the practical challenges and opportunities in implementing nutrient recycling on various scales.

Table 1 summarizes the key focus areas of study in the nine journal articles. This information is complemented by Table 2, situating the focus topic of each of the nine journal articles in the knowledge field and discourse of the "circular economy."

4.1 Technological innovations and challenges

Technological advancements play a central role in the development of RNFs and the eventual uptake and integration within sustainable agricultural practices. Studies such as Duboc et al. (2022), highlight specific innovations in phosphorus recycling technologies, notably struvite precipitation and pyrolysis of sewage sludge. These technologies offer significant potential to recover and concentrate essential nutrients from organic waste streams. However, they also face several technical challenges, including high energy and chemical costs, operational costs, and suboptimal or limited nutrient recovery rates. For instance, scaling up struvite precipitation is problematic due to issues of efficiency of nutrient recovery and the risk of contamination with heavy metals from sewage sludge. Similarly, biochar production has potential for P and potassium (K) recovery, but not N and its widespread adoption is hindered by potential contaminants in the feedstock and the complexity of determining the availability of the nutrients in biochar for plant uptake.

Anaerobic digestion (AD) is another promising technology for nutrient recovery, particularly N & P, yet it is associated with high investment costs, high operational energy demands to transport the waste to the AD plant and the digestate back to the fields. Despite these challenges, AD remains widely researched and applied since the primary focus of AD is biogas production which is a source of green energy. AD is also popular due to its ability to handle diverse organic waste streams, including livestock manure and food and slaughter waste. Innovations in post-digestion nutrient capture methods, such as centrifuge separation, membrane filtration and ammonia stripping are emerging to improve the overall nutrient recovery efficiency in the AD process. In addition to these well-established technologies, new approaches such as electrochemical nutrient recovery, hydrothermal carbonization and microbial electrolysis are under development. While still largely in low technology readiness levels, these methods offer possibilities for increased nutrient recovery with reduced energy consumption and possibly even lower contamination risks.

Collectively, the articles illustrate that the uptake of RNFs into the circular economy framework is facilitated by various technological innovations and the resolution of associated challenges. Looking forward, the technological landscape of nutrient recycling will likely evolve through incremental improvements with existing technologies and eventually with innovated emerging technology breakthroughs. The development of integrated systems that combine multiple technologies may offer solutions to address the limitations of individual processes, such as combining AD with struvite precipitation to enhance nutrient recovery from both liquid and solid fractions. Furthermore, advances in digital tools and automation for precise process monitoring and control could further optimize the efficiency and scalability of these technologies, reducing operational costs and energy consumption.

4.2 Methodological rigor and interdisciplinary approaches

The selected studies emphasize the critical role of methodological rigor and interdisciplinary collaboration in advancing the research and application of RNFs. As described in Section 2, these studies were chosen through a multi-step process, which refined an initial set of over 16,000 publications based on criteria such as full-text availability,

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TABLE 1 Article subject focus for "recycled nutrients".

Author(s)	Year of publication	Technology and policy frameworks	Detailed focus on recycling techniques	Environmental impact considerations	Economic and regional considerations	Contaminants and safety concerns	Nutrient recycling and sustainability	Specificity of nutrient focus
Bünemann et al.	2023	Focus on risk assessment methods for contaminants in recycled fertilizers	Detailed examination of contaminants in recycled fertilizers	Discusses contaminants and their potential risks in organic agriculture	Evaluates the feasibility and safety of using RNFs in organic settings	Discusses contaminants and their potential risks in organic agriculture	Reviews the use of recycled nutrients and their safety in organic agriculture	Specific focus on organic agriculture
Egas et al.	2023	Lacks detailed discussion on specific technologies or policy impacts	General mention of bio-based fertilizers. No specifics on techniques	Extensive focus on the lifecycle impacts of bio-based fertilizers	No detailed economic analysis provided	Extensive focus on the lifecycle impacts of bio-based fertilizers	Emphasizes life cycle assessment for environmental sustainability	General environmental focus; not specific to types of nutrients
Wiel et al.	2023	Broad discussion on challenges and opportunities in recycling technologies and policies	Discusses challenges and opportunities. No specific recycling techniques	Considers systemic environmental impacts of nutrient circularity	No detailed economic or regional considerations	Considers systemic environmental impacts of nutrient circularity	Broad discussion on nutrient circularity and systemic sustainability	No specific focus on particular nutrients; general circularity
Callesen et al.	2022	Examines regional technology and policies impacting nutrient recycling	Examines nutrient recycling from an economic feasibility angle	Limited direct environmental impact discussion; focus on feasibility	Strong focus on economic feasibility of nutrient recycling in the Baltic Sea region	Limited direct environmental impact discussion; focus on feasibility	Discusses recycling nutrients in the context of Baltic Sea region's sustainability	Focuses on regional feasibility, not specific nutrients
Chojnacka et al.	2022	General mention of bio-based production without detailed policy context	General concept of recycling biomass. No in-depth methods	Impacts of using biomass waste for fertilizer production	Lacks regional or economic specificity	Impacts of using biomass waste for fertilizer production	Discusses bio-based fertilizers contributing to sustainability	Focus on bio-based, not strictly recycled nutrients
Duboc et al.	2022	Focus on technological methods to measure phosphorus availability	Concentrated on extraction techniques and their effectiveness	Limited discussion on direct environmental impacts of specific fertilizers	Does not address economic aspects	Limited discussion on direct environmental impacts of specific fertilizers	Analyzes prediction of phosphorus availability in recycling fertilizers	Phosphorus-focused; not covering other nutrients comprehensively
Zhang et al.	2020	No specific focus on technologies or policies for nutrient recycling	No specific focus on recycling methods or technologies	Broad ecological and environmental nutrient budget considerations	No economic analysis related to nutrient management	Broad ecological and environmental nutrient budget considerations	General sustainable nutrient management without focus on recycling	Broad ecological perspective, not specific to recycled products
Akram et al.	2019	In-depth look at Swedish technology and policies for nutrient recycling	Broad discussion on nutrient recycling technologies	General environmental benefits of nutrient recycling discussed	Focuses on Swedish regional applications and policy frameworks	General environmental benefits of nutrient recycling discussed	Covers broad nutrient recycling techniques and sustainability benefits	Not specific to particular nutrients; broad scope
Goulding et al.	2008	No specific policy or technological focus; general management strategies	No detailed examination of specific recycling techniques	Discusses optimizing environmental impacts through better nutrient management	No specific economic considerations discussed	Discusses optimizing environmental impacts through better nutrient management	Strategies for optimizing nutrient use including recycling aspects	Broad optimization techniques, not nutrient-specific

TABLE 2 Article subject focus for "circular economy."

Author(s)	Year of publication	View on circular economy	Role of nutrient recycling	Viable business model	Additional factors
Bünemann et al.	2023	Discusses the safety and sustainability of using recycled nutrients in organic agriculture.	Critical for sustainable organic farming, but raises concerns about contaminants.	Highlights the potential market for safe, contaminant-free recycled nutrients in organic agriculture.	Emphasizes the need for stringent contaminant screening and regulatory standards.
Egas et al.	2023	Highlights sustainable practices through life cycle assessments to support circular economy approaches.	Implicit support for recycling by focusing on bio-based materials in production cycles.	Lacks detailed economic discussion but suggests regulatory frameworks could support business opportunities.	Impact of regulatory frameworks on market access and adoption.
Wiel et al.	2023	Focuses on system-wide innovations for achieving circularity in nutrient management.	Crucial for reducing dependencies on imported nutrients and enhancing local sustainability.	Highlights the need for new business models to make circularity economically viable.	Cross-sector collaboration and development of supportive policy frameworks.
Callesen et al.	2022	Discusses nutrient recycling within a regional context, aligning with circular economy principles.	Focuses on nutrient recycling in the Baltic Sea region for regional sustainability.	Analyzes economic feasibility, noting challenges and potential for viable business models.	Regional focus, exploring the balance between economic feasibility and environmental impact.
Chojnacka et al.	2022	Promotes the role of bio-based fertilizers in the circular economy by using biomass for nutrient recovery.	Central to the theme, emphasizing nutrient recycling from biomass for sustainability.	Suggests economic viability through biomass valorization, creating value-added products from waste.	Technological advancements and regulatory support needed for market adoption.
Duboc et al.	2022	Supports principles of the circular economy by focusing on effective recycling techniques for phosphorus.	Focuses on maximizing resource efficiency through phosphorus recycling.	Does not discuss business models, focusing on the technical aspects of phosphorus recovery.	Needs for technological innovation in recycling methods.
Zhang et al.	2020	Discusses circular approaches in nutrient management without explicitly using the term "circular economy."	Advocates for sustainable nutrient management and recycling within ecosystems.	No detailed economic analysis; focuses more on ecological and management practices.	Broader ecological and system-level implications.
Akram et al.	2019	Views circular nutrient management as essential but indicates challenges in achieving effective local recycling.	Emphasizes the need for better nutrient management and local recycling strategies.	Discusses economic aspects, suggesting potential financial benefits with changes in market conditions.	Considerations of economic scale, local vs. long-distance recycling viability.
Goulding et al.	2008	Implies support for circular economy through nutrient management strategies that include recycling.	Discusses optimizing nutrient use, including recycling, for better environmental outcomes.	Lacks detailed discussion on business models, focusing on optimization rather than economic implications.	Optimization techniques and their impact on sustainability.

open access, language, review nature, and methodological diversity. This selection ensured a broad representation of research methodologies and perspectives, providing comprehensive insights into the technological, environmental, economic, and policy dimensions of nutrient recycling. Employing diverse methodologies, including experimental designs, Life Cycle Assessments, and regional case studies, these studies highlight the importance of robust scientific approaches to ensure the effectiveness and safety of RNFs, as well as their alignment with circular economy goals.

Bünemann et al. (2024) and Duboc et al. (2022) emphasize the need for advanced analytical techniques to monitor contaminant levels and ensure the quality of RNFs. Rigorous methodologies are essential for meeting health standards and addressing safety concerns, thus ensuring that RNFs can be used. Interdisciplinary approaches, as highlighted by Egas et al. (2023) and van der Wiel et al. (2023) combine environmental science, economics, and agricultural engineering to evaluate lifecycle impacts and economic viability of RNFs. This holistic perspective is vital for developing sustainable nutrient recycling practices that are economically viable and environmentally sound.

Methodological diversity is crucial to understand the complex interactions between agricultural practices, environmental impacts, and economic factors. Advances in interdisciplinary modeling and data synthesis are needed to address these complexities and improve the practical application of nutrient recycling strategies. By fostering methodological rigor and interdisciplinary collaboration, these studies provide a robust foundation for developing innovative and effective RNF solutions, supporting the circular economy's goals of resource efficiency, waste reduction and agricultural sustainability.

4.3 Environmental and economic implications

The integration of RNFs within the circular economy framework presents a significant opportunity for reducing the environmental impact of agricultural practices while promoting regional economic sustainability. Studies by Egas et al. (2023) and van der Wiel et al. (2023) provide robust evidence that RNFs typically exhibit a lower environmental footprint compared to synthetic fertilizers. Life cycle assessments from these studies demonstrate that RNFs contribute to reduced global warming potential and lower fossil energy consumption. This is largely due to their reliance on waste materials that would otherwise end up in landfills, contributing to methane emissions and other environmental hazards. By recovering nutrients from organic waste streams, RNFs help close nutrient loops, thus aligning with the principles of circular economy which emphasizes resource efficiency and waste minimization.

Life Cycle Assessments, such as those conducted by Callesen et al. (2022) and Chojnacka et al. (2020), quantify the environmental benefits of RNFs compared to synthetic fertilizers, while policy and economic analyses by Akram et al. (2019) and Goulding et al. (2008) explore the role of supportive policies and incentives for promoting RNF adoption. Regional studies, like those by Zhang et al. (2020) and Akram et al. (2019), demonstrate the importance of tailoring nutrient recycling practices to local conditions, which is key to maximizing their effectiveness.

One of the major environmental advantages of RNF's is their ability to improve soil health by adding organic matter and stimulating microbial activity (Bot and Benites, 2005). This not only enhances soil fertility but also promotes biodiversity and strengthens ecosystem resilience, as highlighted by van der Wiel et al. (2023). However, the environmental benefits of RNFs must be carefully balance with the challenges posed by potential contaminants. Studies indicate that heavy metals, organic pollutants, and pathogens can be present in some recycled nutrients, posing risks to soil and water quality if not effectively managed. Addressing these contamination risks is crucial to ensuring that RNFs deliver on their environmental promise without introducing new ecological problems.

Economically, the feasibility of recycled nutrient technologies varies depending on the waste stream, the nutrients of interest, type of technology and its associated costs. AD, for example, offers a favorable economic profile because it generates biogas, which can offset the costs of nutrient recovery and provide an additional revenue stream for farmers and waste managers. However, other technologies with high capital and operational costs, limit widespread adoption. Additionally, fluctuations in the quality and consistency of RNFs can make them less competitive in the market compared to synthetic fertilizers, which offer more predictable quality and performance. van der Wiel et al. (2023) and Callesen et al. (2022) highlight that market barriers, such as high upfront investment costs and limited farmer acceptance continue to impede the economic viability of RNFs.

Despite these challenges, the potential for cost saving through waste reduction and the circular use of resources remains a significant economic advantage of RNFs. By transforming waste streams into valuable inputs for agriculture, RNFs reduce the costs associated with waste disposal and synthetic fertilizer production. However, for these economic benefits to be fully realized, improvements in the efficiency and scalability of nutrient recovery technologies are essential. Further research is needed to optimize processes that reduce energy consumption and operational costs, making RNFs more accessible and competitive in the agricultural market. Research should also explore how fluctuations in quality and availability of the RNFs affect their market competitiveness and adoption.

4.4 Contaminants and safety concerns

Contaminants in RNFs present a significant challenge to ensure their safe use in agriculture. As Bünemann et al. (2024) notes, the waste stream being processed and the nutrient recovery methods influence contamination risks: selective nutrient extraction can yield lower contaminant levels, while broader recovery practices may increase the presence of harmful substances. Ensuring the safety of RNFs requires minimizing contaminants such as heavy metals, organic pollutants, and pathogens which can threaten soil health, crop safety and human health through bioaccumulation in food chains (van der Wiel et al., 2023).

Advanced treatment technologies, such as thermal processing and chemical extraction, can reduce contaminants, but they come with high costs and energy demands (Egas et al., 2023). These trade-offs between safety and economic feasibility complicate their widespread adoption. Emerging contaminants like microplastics and antibiotic resistance genes represent new areas of concern, with uncertain long-term effects on ecosystems, necessitating ongoing research and monitoring (Bünemann et al., 2024).

Regulatory frameworks play a key role in managing contamination risks by setting safety standards. However, overly stringent regulations can hinder innovation in nutrient recycling technologies (Duboc et al., 2022). Balancing safety with technological advancement is essential. Chojnacka et al. (2020) suggests that integrating contaminant management into the design of recycling processes can enhance safety, proposing bioremediation and phytoremediation as potential strategies to degrade or immobilize contaminants. Regular monitoring and risk assessment, as emphasized by Akram et al. (2019), are critical to ensuring that RNFs meet safety standards throughout their lifecycle.

4.5 Policy and regulatory framework

The uptake and use of RNFs are significantly influenced by the strength and structure of policy and regulatory frameworks. Localized strategies and supportive regulations are essential to ensure both environmental safety and the market viability of RNFs. For example, the Revaq certification in Sweden, as highlighted by Callesen et al. (2022), has successfully minimized harmful substances in sewage sludge while promoting safe recycling on agricultural land. This demonstrates the importance of targeted policies that enable the safe use of recycled nutrients. However, strict regulation, such as the EU stringent regulations on allowable contaminants can limit innovation and the range of permissible RNFs for market. Bünemann et al. (2024) and Duboc et al. (2022) note that while these regulations protect soils and the environment, they may also hinder technology progress and broader adoption of nutrient recycling. Policies that incentivize the use of RNFs and more specifically the replacement of industrially produced mineral fertilizers could be more effective in creating a market demand for RNFs.

To foster sustainable nutrient recycling, policy adjustments are needed to balance safety with innovation. Flexible frameworks that encourage experimentation while maintaining environmental standards can stimulate technological development. Economic incentives, such as subsidies, tax breaks, and certification schemes, are also crucial (van der Wiel et al., 2023; Egas et al., 2023). Studies by Chojnacka et al. (2020) and Akram et al. (2019) show how these financial tools reduce the costs for farmers and waste managers, making RNFs more competitive with synthetic fertilizers and supporting their integration into systems for sustainable agriculture. Integrating nutrient recycling into broader circular economy strategies creates a coherent policy environment, aligning RNFs with resource efficiency and waste reduction goals. Additionally, international cooperation, as suggested by Goulding et al. (2008) and Zhang et al. (2020), is essential for harmonizing regulations and creating unified standards. Such collaboration can expand markets and facilitate the wider use of RNFs.

A multi-faceted policy approach is crucial for promoting RNFs within the circular economy framework. Including regulatory flexibility for innovation, financial incentives for economic viability, and international collaboration to harmonize standards. By addressing these areas, policy frameworks can drive the adoption of RNFs, reduce dependence on synthetic fertilizers, and support recycling of organic waste into valuable agricultural inputs.

4.6 Farmer acceptance and public perception

Farmer acceptance and public perception play crucial roles in the adoption of RNFs, particularly those derived from sewage sludge or industrial waste streams, which are often met with skepticism. Concerns about potential contaminants, such as heavy metals, pathogens, and microplastics, raise questions about the safety and quality of these fertilizers. Many farmers may be hesitant to adopt RNFs due to fears of soil contamination, reduced crop quality, or regulatory burdens. Similarly, consumers may harbor concerns about the safety of food produced using fertilizers derived from waste materials, which can further influence market dynamics.

Building trust through transparency, rigorous safety standards, and clear communication is essential to overcoming these barriers. Studies have shown that when safety and efficacy are demonstrated through scientific evidence, alongside strong regulatory frameworks, farmer acceptance improves. Public awareness campaigns highlighting the environmental benefits of RNFs, such as their role in reducing waste and closing nutrient loops within the circular economy, can also help shift perceptions. Encouraging open dialogue among stakeholders—farmers, scientists, policymakers, and consumers—will be key to fostering greater acceptance of recycled nutrients as part of a sustainable agricultural system.

4.7 Spatial and logistical considerations

Within the circular economy framework, addressing contaminants is vital to safely close nutrient loops. By integrating effective contaminant management, innovative treatment technologies and flexible regulatory oversight, RNFs can be safely incorporated into sustainable agricultural practices, reducing waste while protecting human and environmental health.

Spatial and logistical considerations are crucial to the effective integration of RNFs into agricultural systems. As Akram et al. (2019) notes, the spatial separation between regions of livestock, municipalities, industrial areas and crop production creates nutrient imbalances with some areas in surplus and others in deficit. Nutrient-rich manure from livestock operations generally creates areas of nutrient surplus which is often located in different areas than crop-producing areas that need the nutrients and are thus in deficit. Transporting bulky materials like manure, sludge or digestate from AD is both costly and logistically complex, as discussed by Akram et al. (2019) and Callesen et al. (2022). These challenges are compounded by lack of infrastructure for processing and storing recycled nutrients on many farms.

Localized processing facilities, as suggested by van der Wiel et al. (2023), can help address these challenges by converting organic waste into high-quality fertilizers near the source, reducing transport costs and improving nutrient availability for nearby farms. Additionally, matching the seasonal and crop-specific nutrient demand with the supply of recycled nutrients is another logistical issue, requiring improved system to quantify and predict nutrient flows, as emphasized by Bünemann et al. (2024) and Duboc et al. (2022).

Effective policies that promote regional collaboration and provide incentives for infrastructure development, such as transport and localized processing facilities, are essential for improving the logistics of nutrient recycling. As highlighted by Goulding et al. (2008) and Zhang et al. (2020), coordination among stakeholders can facilitate the establishment of localized systems. Addressing these spatial and logistical issues is key to successfully integrating RNFs into the circular economy, helping to close nutrient loops, reduce waste and improve resource use efficiency.

5 Conclusion

This mini review has demonstrated how RNFs are an integral part of the circular economy. Despite challenges associated with their uptake, the reviewed studies provide a comprehensive understanding of the current state and potential of RNFs, highlighting both advancements and ongoing obstacles. They emphasize the need for continued technological innovation, supportive policy frameworks, effective contaminant management, and interdisciplinary approaches to fully unlock the benefits of nutrient recycling in sustainable agriculture. By embedding nutrient recycling within the circular economy, these efforts not only promote the reuse of societal waste streams but also reduce dependence on finite mineral and fossil fuel resources and mitigate environmental impacts. This alignment with circular economy principles shows that with the right strategies, RNFs can significantly contribute to a more sustainable and resilient agricultural system.

Author contributions

CC: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. ES: Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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