Interreg Baltic Sea Region

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CIRCULAR ECONOMY

CiNURGi

Circular Nutrients for a Sustainable Baltic Sea Region (CiNURGi)

Draft industry standards for quality assurance of recycled nutrient fertilizers

This #MadeWithInterreg project helps drive the transition to a green and resilient Baltic Sea region and is part of the EU-funded Interreg Baltic Sea Region (BSR) core project #C049, titled CiNURGi, under the 2021-2027 PROGRAMME, Priority 3: Climate-Neutral Societies, Objective 3.1: Circular Economy.

Organisations from the following countries cooperate together to make that happen: Sweden (LP), Denmark, Estonia, Finland, Germany, Latvia, Lithuania and Poland.

Project homepage: https://interreg-baltic.eu/project/cinurgi
Project LinkedIn page: https://www.linkedin.com/showcase/cinurgi

Foreword

CiNURGi (Circular Nutrients for a Sustainable Baltic Sea Region) is an Interreg BSR Core Project dedicated to advancing circular economy for nutrients within the Baltic Sea Region. By enhancing infrastructure, technology, and policy the project seeks to improve nutrient recovery from biomass and resource streams originating from agricultural, municipal, and industrial sources. This endeavor aligns with several regional and European strategies, including the HELCOM Baltic Sea Regional Nutrient Recycling Strategy, the EU's Circular Economy Action Plan under the Green Deal, and the Integrated Nutrient Management Action Plan of the Farm to Fork Strategy. The CiNURGi is ongoing from November 2023 to October 2027.

*This report pertains to **Work Package 1, Task 1.2**, which focuses on the development of draft industry standards for evaluation and quality assurance of recycled nutrient fertilisers (RNFs). The task aims to define scientifically robust and practically applicable assessment schemes for nutrient effectiveness, contaminant safety, physical and technical quality, and compliance with EU and regional requirements. In doing so, it contributes directly to CiNURGi's overarching goals by enabling the safe and efficient recycling of nutrients across borders and by supporting policy implementation in the Baltic Sea Region.*

We acknowledge the collaborative efforts of our consortium, comprising 24 partners and 13 associated organizations from Denmark, Estonia, Finland, Germany, Poland, Latvia, Lithuania, and Sweden. Their dedication and expertise are instrumental in driving the project's success.

For more information about CiNURGi and its initiatives, please visit our project homepage https://interreg-baltic.eu/project/cinurgi/

September 2024

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Executive Summary

This report presents draft industry standards for the evaluation and quality assurance of recycled nutrient fertilisers (RNFs), which were developed within the framework of the CiNURGi project. The objective is to provide a scientifically robust and practically applicable framework that ensures the safe, effective, and sustainable use of RNFs in agriculture. The standards integrate several quality dimensions, including hygienisation and stability, nutrient availability, contaminant control, and physical as well as practical quality. By combining these aspects, the framework allows for a comprehensive assessment that links product safety and regulatory compliance with technical usability and agronomic performance.

The report emphasises the importance of hygienisation and stability criteria to guarantee pathogen safety and biological maturity, nutrient availability parameters to assess plant uptake and solubility of macro- and micronutrients, and contaminant control to evaluate heavy metals, organic pollutants, antibiotics, and physical impurities in relation to nutrient contents. In addition, physical and practical properties such as storability, transportability, and applicability are considered essential for determining whether RNFs can be reliably handled, transported, and applied under farm conditions.

The proposed standards are designed to complement and operationalise the EU Fertilising Products Regulation (EU 2019/1009) while addressing specific requirements of the Baltic Sea Region, where nutrient recycling is directly linked to environmental protection goals. By providing transparent, harmonised criteria for RNFs, this report contributes to the broader objectives of the CiNURGi project by supporting circular nutrient management, strengthening regulatory implementation, and enhancing farmer and industry confidence in RNFs as a safe and competitive alternative to mineral fertilisers.

Keywords: Recycled nutrient fertilisers (RNFs), Quality assurance, Nutrient availability, Contaminant control, Hygienisation and stability, Physical and practical quality, Fertilising Products Regulation, Circular economy

Executive summary (German)

Dieser Bericht stellt Entwürfe für Industriestandards zur Bewertung und Qualitätssicherung von Recyclingdüngern (RNF) vor, die im Rahmen des CiNURGi-Projekts erarbeitet wurden. Ziel ist es, einen wissenschaftlich fundierten und praxisnah anwendbaren Bewertungsrahmen bereitzustellen, der eine sichere, wirksame und nachhaltige Nutzung von RNF in der Landwirtschaft gewährleistet. Die vorgeschlagenen Standards berücksichtigen zentrale Qualitätsdimensionen wie Hygienisierung und Stabilität, Nährstoffverfügbarkeit, Kontrolle von Kontaminanten sowie physikalische und praktische Produkteigenschaften. Durch die Integration dieser Aspekte wird eine umfassende Bewertung ermöglicht, die Produktsicherheit und regulatorische Anforderungen mit technischer Gebrauchstauglichkeit und agronomischer Leistungsfähigkeit verbindet.

Besonderes Gewicht wird auf Hygienisierung und Stabilität gelegt, um Pathogensicherheit und biologische Reife sicherzustellen. Die Nährstoffverfügbarkeit wird über die pflanzliche Aufnahme und die Löslichkeit von Makro- und Mikronährstoffen erfasst. Die Kontrolle von Kontaminanten umfasst die Bewertung von Schwermetallen, organischen Schadstoffen, Antibiotikarückständen und physikalischen Verunreinigungen in Relation zum Nährstoffgehalt. Darüber hinaus werden physikalische und praktische Eigenschaften wie Lagerfähigkeit, Transportierbarkeit und Anwendbarkeit als entscheidend angesehen, um sicherzustellen, dass RNF zuverlässig gelagert, verteilt und mit gängiger Technik ausgebracht werden können.

Die vorgeschlagenen Standards ergänzen die Anforderungen der EU-Düngeprodukteverordnung (EU 2019/1009) und gehen zugleich auf die besonderen Bedingungen der Ostseeregion ein, in der das Nährstoffrecycling eng mit Zielen des Umweltschutzes verbunden ist. Mit der Bereitstellung transparenter und harmonisierter Kriterien leistet dieser Bericht einen direkten Beitrag zu den Zielen des CiNURGi-Projekts, indem er das kreislauforientierte Nährstoffmanagement stärkt, die Umsetzung regulatorischer Vorgaben unterstützt und das Vertrauen von Landwirtschaft und Industrie in RNF als sichere und wettbewerbsfähige Alternative zu Mineraldüngern erhöht.

Keywords: Recyclingdünger (RNF); Qualitätssicherung; Nährstoffverfügbarkeit; Kontrolle von Schadstoffen; Hygienisierung und Stabilität; physikalische und praktische Produkteigenschaften; EU-Düngeproduktevereordnung; Kreislaufwirtschaft

List of Abbreviations

AMR – Antimicrobial Resistance
AT_4 – Static Respiration Activity (biodegradability index, mg O_2/g OM over 4 days)
BMP – Biochemical Methane Potential (L biogas/g VS)
BSR – Baltic Sea Region
CAT – Calcium Acetate Lactate (extraction method for nutrients)
CE – Conformité Européenne (EU conformity marking)
CMC – Component Material Category (as defined in EU 2019/1009)
Corg – Organic Carbon
CTR – Cumulative Toxin Rating
DM – Dry Matter
DTPA – Diethylenetriaminepentaacetic Acid (extractant for micronutrients)
EC – Electrical Conductivity
EU – European Union
GSI – Granulometric Spread Index
NA – Nutrient Availability
NAP – Nutrient Availability for Phosphorus
OM – Organic Matter
OUR – Oxygen Uptake Rate
PFC – Product Function Category (as defined in EU 2019/1009)
POP – Persistent Organic Pollutants
QA – Quality Assurance
RNF – Recycled Nutrient Fertiliser
SGN – Size Guide Number
TR – Toxin Rating
UI – Uniformity Index
VS – Volatile Solids
WHO-TEQ – World Health Organization Toxic Equivalents

1 Introduction

Nutrient recycling is a key element of the EU's circular economy strategy, helping to reduce dependence on finite mineral fertilisers by recovering valuable nutrients from agricultural, municipal, and industrial waste streams. This concept is embedded in the Baltic Sea Regional Nutrient Recycling Strategy, adopted by HELCOM in 2021, which outlines a vision where nutrient flows are sustainably managed to maintain agricultural productivity while minimizing nutrient loss to the Baltic Sea (HELCOM, 2021). The strategy promotes nutrient reuse, in the form of biomass or nutrient-rich matter, to keep nutrients within productive cycles rather than allowing them to become environmental pollutants.

In research and practice, several terms define nutrient recapture pathways. Nutrient Recycling (NR) refers broadly to the return of biomass-derived nutrients to plants, aligning with HELCOM's framing. Recycled Nutrient Fertilisers (RNFs) describe fertilisers made from secondary sources like manure, organic waste, sewage sludge, or industrial by-products, as defined in the CiNURGi (INTEREG BSR) project. Bio-Based Fertilisers (BBFs) denote fertilisers derived from organic biomass (plant, animal, or microbial origin), with industry recommendations suggesting that products with less than 80-90% bio-based nutrient content may be more accurately labelled as "Partly Bio-Based" (ESPP, 2023; CEN, 2014). Other terms, such as Alternative Fertilisers (AF), are used in EU Horizon programs like FERTITEC and FERTICOVERY to denote fertilisers derived from secondary raw materials.

RNFs contribute to sustainability by turning waste into valuable agricultural inputs, thereby closing nutrient cycles, reducing reliance on fossil-resource-based mineral fertilisers, and lowering environmental impacts. However, this diversity of sources requires strict safety, efficacy, and environmental regulations. Key regulations include (EC) No 1069/2009 and (EU) No 142/2011, governing animal by-product-derived fertilisers; (EU) 2021/1165, regulating digestates for organic farming; and (EU) 2019/1009, which sets the EU-wide framework for marketing fertilising products, including organic and recycled outputs. Recently adopted (EU) 2024/3019 further expands the permissible use of certain wastewater treatment fractions as fertilisers.

Industry standards reinforce regulatory requirements by establishing benchmarks for safety, performance, and environmental compliance. Harmonizing these standards with legal frameworks builds trust and supports the responsible integration of RNFs into agriculture, promoting innovation, improving sustainability, and enabling confidence in circular nutrient solutions.

1.1 Guaranteeing Product Safety

Ensuring the safety of recycled nutrient fertilizing products (RNFs) is essential for environmental protection and human health. Acceptance by users and consumers depends on evidence-based standards that set enforceable contaminant thresholds, prevent accumulation in agricultural soils, and safeguard food safety. The HELCOM Baltic Sea Action Plan action E33 calls for the development of RNF safety requirements by 2027 and for the minimization of harmful compounds to ensure compliance. This deliverable provides the basis for that work and supports Objective 3 of the HELCOM Baltic Sea Regional Nutrient Recycling Strategy, which focuses on safe nutrient recycling through risk minimization and knowledge sharing. The first sub-objective aims to reduce risks to human health and the environment from contamination and requires greater awareness of hazards associated with processing and reusing diverse biomasses. Key concerns include inorganic harmful substances such as heavy metals, organic pollutants including persistent organic pollutants, and hygiene related risks from pathogens. Establishing and strengthening science-based limit values and quality criteria is necessary for the safe production and use of RNFs. The second sub-objective promotes research and the exchange of best practices for safe RNF use. Active stakeholder engagement is needed to raise awareness of health and safety aspects and to encourage effective risk mitigation strategies. A core function of industry standards is to define clear and enforceable thresholds for contaminants in RNFs. These include potentially toxic elements such as lead, chromium, cadmium, and mercury, metalloids such as arsenic, persistent organic pollutants such as dioxins and furans and perfluorinated compounds, and harmful pathogens including Salmonella and Escherichia coli. By setting these limits, standards help prevent unintended accumulation of toxic substances in soils, protect human health, ecosystems, and groundwater, and support crop quality and food safety.

1.2 Ensuring Nutrient Efficacy

RNFs must be safe and agronomically effective. Industry standards specify minimum requirements for essential nutrients, in particular nitrogen, phosphorus, and potassium (NPK nutrients), so that RNF products support plant growth and soil fertility. They also require accurate labelling of NPK contents, which promotes transparency and enables farmers to make informed choices based on reliable and comparable information. Clear nutrient thresholds help maximize yields, maintain soil health, and ensure consistent product performance.

1.3 Supporting Regulatory Compliance

Regulatory compliance is a prerequisite for successful market integration of RNFs at national and international levels. Where national rules govern RNF production and application, they must be followed to achieve market acceptance. Harmonized international standards reduce regulatory differences and support trade by lowering barriers for producers and by aligning product quality. For example, using evaluation methods that are consistent with European Union fertiliser regulations or other widely recognized frameworks enables a unified approach to RNF production and use. Such harmonization creates a level playing field for manufacturers, improves regulatory transparency, and simplifies market entry for innovative products. It also reassures stakeholders, including farmers, regulators, and consumers, about the safety, efficacy, and environmental benefits of RNFs. By combining adherence to national requirements with the advantages of international alignment, compliance efforts can serve local agricultural priorities while advancing sustainable nutrient management across borders.

1.4 Promoting Environmental Sustainability

RNFs should align with environmental sustainability. By encouraging the recycling of organic and inorganic wastes into fertilisers, RNF standards support sustainable waste management and reduce dependency on landfills. By providing alternatives to mineral fertilisers, RNFs can lower the environmental footprint of agriculture, including greenhouse gas emissions associated with fertiliser production. Where organic matter is present, RNFs can also enhance soil health and plant growth through improved soil structure and biological activity.

2 Classification and Legal Framework for RNF under EU Regulation

The European Union's Regulation (EU) 2019/1009 governs the classification and assessment of all fertilising products, including recycled nutrient fertilisers (RNFs). Adopted on 5 June 2019, it replaced Regulation (EC) No 2003/2003 as of 16 July 2022, broadening product scope to include organic and organo-mineral fertilisers, soil improvers, growing media, inhibitors, plant biostimulants, and blends—all with the aim to harmonize safety, quality, and labelling standards, foster circular economy, and encourage trade across Member States (European Parliament & Council, 2019). Similarly, Germany's Fertiliser Ordinance (DüMV) applies to all fertilisers, soil improvers, growing media, and plant aids, aligning with this broad EU framework rather than limiting its scope to RNFs.

2.1 Component Material Categories (CMCs)

CMCs, listed in the Annex II of the EU Regulation, specify permitted material origins and processing routes for fertiliser ingredients. An EU CE-marked product must be formulated from one or more valid CMCs and correspond to a functional class (PFC) in Annex I (European Parliament & Council, 2019).

Relevant CMCs for RNFs include:

CMC 3. Compost. Compost derived from separately collected plant-based inputs.

CMC 4. Fresh-crop digestate. Fresh-crop digestate from anaerobic digestion of plant-only biomass.

CMC 5. Digestate other than fresh-crop digestate. Digestate from mixed organic sources, such as manures, food waste, and residues.

CMC 6. Food industry by-products. Food industry by-products such as molasses and distillers' grains.

CMC 10. Derived products from animal by-products (e.g., processed manure, bone meal).

CMC 11. By-products as defined under the Waste Framework Directive. Industrial by-products under the Waste Framework Directive

CMC 12. Precipitated phosphate salts and their derivates. Phosphorus products wastewater.

CMC 13. Thermal oxidation materials and derivates. Materials obtained from eligible ash streams.

CMC 14. Pyrolysis and gasification materials. Biochar-type materials from controlled thermal conversion of eligible organic inputs.

CMC 15. Recovered high-purity materials. Examples include ammonium salts or calcium nitrate recovered from process streams.

These categories provide necessary flexibility for capturing a wide array of nutrient recycling pathways within a harmonized regulatory framework.

2.2 Product Function Categories (PFCs)

Annex I sets out PFCs, defining the intended role of each fertilising product. To obtain CE-marking, a product must fall under one PFC and comply with its corresponding composition, and labelling requirements (European Parliament & Council, 2019).

PFC 1. Fertilisers. Products that supply nutrients to plants.

PFC 1(A) Organic fertilisers. Organic nutrient sources, often formulated from composts, digestates, or animal-derived materials when they meet the nutrient and organic carbon minima for this PFC.

PFC 1(B) Organo-mineral fertilisers. Products that combine organic and mineral nutrient fractions.

PFC 1(C) Inorganic fertilisers. Mineral products, including those produced from recovered high-purity nutrients.

PFC 1(C)(I) Inorganic macronutrient fertilisers. Products supplying nitrogen, phosphorus, potassium or their combinations in mineral form.

PFC 1(C)(II) Inorganic micronutrient fertilisers. Products supplying trace elements such as iron, manganese, zinc, copper, boron or molybdenum in mineral form.

PFC 2. Liming materials. Products that correct soil acidity with calcium or magnesium compounds.

PFC 3. Soil improvers. Products that improve physical, chemical, or biological soil properties.

PFC 3(A) Organic soil improvers. For example, compost-based or biochar-based improvers that primarily improve soil properties rather than supply nutrients.

PFC 3(B) Inorganic soil improvers. For example, mineral amendments or certain ash-based products.

PFC 4. Growing media. Media in which plants grow. These can contain recycled constituents but their primary function is not nutrient supply.

PFC 5. Inhibitors. Products that delay nutrient transformation or release, for example nitrification or urease inhibitors. Relevance to RNF is limited since these are typically not recycled nutrient sources.

PFC 6. Plant biostimulants. Products that stimulate plant nutrition processes independently of the product's own nutrient content. Microbial or non-microbial. Usually outside RNF scope.

PFC 7. Fertilising product blends. Blends of two or more PFC products.

RNF most often fall under PFC 1 and PFC 3, and in some cases under PFC 7 when blended. PFC 4, PFC 5, and PFC 6 are usually outside the RNF scope because their primary function is not nutrient recovery or nutrient supply.

To market an RNF as an EU fertilising product, the composition must be built from eligible CMC materials and the finished product must comply with a PFC. Labelling must follow Annex III and conformity assessment must follow Annex IV. This combined approach ensures safety, performance, and transparent information while enabling cross-border market access for recycled nutrient products.

3 Production Techniques for RNFs

Producing Recycled Nutrient Fertilisers (RNFs) involves converting nutrient-rich secondary materials into standardized, safe and easy-to-use agricultural inputs. This process aims to enhance nutrient concentration, improve transportability and storage, and maintain environmental and economic efficiency. The choice of processing route depends on the nature of input materials, the desired end-product, regulatory constraints, and market preferences.

3.1 Processing Levels: from simple to sophisticated

Basic processing methods are cost-effective, energy-efficient, and relatively easy to implement. Common methods include composting and anaerobic digestion. Although they deliver low-cost outputs with moderate nutrient concentration, they often result in variable product composition and lower nutrient availability (Martín-Sanz-Garrido et al., 2025; Chojnacka & Moustakas, 2024). In many cases it is followed by intermediate processing.

Intermediate processing encompasses methods such as drying and pelletising, granulation, and precipitation. These enhance nutrient concentration, handling, and storage, delivering more uniform products at moderate costs.

Advanced processing includes high-tech treatments like thermal hydrolysis, hydrothermal carbonisation (HTC), gasification, and hydrothermal liquefaction (HTL). These approaches maximise nutrient recovery, significantly improve homogeneity, and reduce contaminants. Ensure, however, that they come with high investment and energy needs (Xu et al., 2024; Cordeiro & Sindhøj, 2024).

Table 1 offers an overview of these processing levels and their trade-offs.

Table 1. Indicative classification of processing levels in recycled nutrient fertiliser (RNF) production according to technological complexity and energy demand.

Processing Level	Techniques	Advantages	Disadvantages
Basic (biological)	Composting, Anaerobic Digestion	Low cost, low energy use, simple implementation	Lower nutrient concentration, variable product composition
Intermediate (mechanical/physico-chemical)	Drying and Pelletising, Granulation, Precipitation	Improved nutrient concentration, better handling and storage	Moderate production costs and energy demand
Advanced (thermo-chemical)	Thermal Treatment, Hydrothermal Carbonisation (HTC), Gasification	High nutrient recovery, consistent product quality	High costs, complex technology, high energy demand

4 Stability criteria of RNFs

Stability is a key prerequisite for the safe handling and effective use of RNFs that contain biodegradable organic matter. Without sufficient stabilisation, residual microbial activity can continue after production, leading to oxygen consumption, heating, gas formation and odour emissions during storage or following field application. Such processes may compromise workplace safety, reduce nutrient efficiency and even cause phytotoxic effects on crops. Stable RNF therefore represent a fundamental requirement for product maturity, agronomic reliability and market acceptance.

In Regulation (EU) 2019/1009, stability is not defined at finished-product level in general, but is linked to the CMCs**.** Only compost (CMC 3) and digestates (CMC 4 and 5) are subject to binding stability tests. Other materials, such as mineral fertilisers, liming products or inorganic soil improvers, fall outside stability control because they contain no biodegradable organic matter. If compost or digestates are used in a fertilising product, they must pass stability testing before the product can obtain CE-marking, regardless of whether the final product is classified as fertiliser, soil improver, growing medium or blend. For compost (CMC 3) stability can be demonstrated by either a low oxygen uptake rate (OUR) or by a sufficient self-heating index (Rottegrad). For digestates (CMC 4 and 5) the alternative to OUR is the residual biogas potential (BMP), which measures the potential for further gas formation under anaerobic conditions. The limits are harmonised and summarised in Table 2.

Table 2. Stability criteria for compost (CMC 3) and digestates (CMC 4/5) according to Regulation (EU) 2019/1009

CMC	Criterion A	Criterion B
Compost (CMC 3)	OUR ≤ 25 mmol O_2/kg OM/h	Rottegrad ≥ III
Digestates (CMC 4/5)	OUR ≤ 25 mmol O_2/kg OM/h	BMP ≤ 0.25 L/g VS

CMC = component material categories; OM = organic matter; VS = volatile solids. Spell out OUR

These criteria apply at the component level but extend to all product function categories (PFCs) in which compost or digestates are used, most notably organic fertilisers (PFC 1(A)), organo-mineral fertilisers (PFC 1(B)), organic soil improvers (PFC 3(A)), growing media (PFC 4) and blends (PFC 7). The stability requirements fulfil three functions. They certify maturity, ensuring that degradable organic fractions have been sufficiently processed and thus reducing the risk of phytotoxic compounds or heating. They enhance safety, by minimising uncontrolled microbial activity and emissions during storage and application. And they enable regulatory compliance, since harmonised and auditable criteria provide a reliable basis for CE-marking and for cross-border trade of RNF in the internal market. Although only OUR, Rottegrad and BMP are defined in the regulation, further indices such as the AT_4 test or the dynamic respiration index are widely used in technical standards and voluntary certification schemes. These parameters can offer additional insights into biological stability and nutrient turnover, but they cannot substitute for the legal thresholds required under Regulation (EU) 2019/1009.

National Variations of Stability criteria of RNFs

While the EU Fertilising Products Regulation (2019/1009) provides harmonised stability criteria for compost and digestates, some Member States apply additional or alternative measures. **Germany**, for example, supplements the EU requirements with extra stability assessments, notably the Dewar self-heating test, which evaluates the biological reactivity of compost and digestate to ensure safe storage and handling. **Poland** also defines its own stabilisation benchmarks: compost or digestate is considered stable if the AT_4 respiration activity is below

10 mg O_2 per gram of dry matter, or if the dry mass loss at 550 °C is less than 35%, or the total organic carbon (TOC) content falls below 20%. These national provisions reflect a more detailed approach to assessing biological maturity and reducing environmental risks.

5 Importance of Hygienisation in Evaluating RNF

Hygienisation is central to the safe, high-quality and environmentally compatible use of RNF in the EU. It comprises controlled treatment steps that inactivate pathogens, reduce residual microbial activity and ensure that products containing biodegradable organic matter can be handled, stored and applied without creating health risks or unwanted emissions. This is particularly relevant where inputs originate from waste streams or from plant and animal materials that may carry microorganisms of concern if untreated.

The objectives are threefold: protection of public and animal health by breaking infection pathways, safeguarding of soils and waters by preventing the introduction and spread of harmful microorganisms, and improvement of product stability and marketability through a harmonised, auditable safety baseline.

Under Regulation (EU) 2019/1009, hygienisation requirements are tied both to eligible CMC and to finished product categories (PFC). Annex I sets microbiological endpoints that the final product must meet, most notably absence of *Salmonella* in 25 g and limits for *E. coli* or Enterococcaceae, while Annex II recognises process routes for specific CMC as achieving hygienisation. Thus, CMC 3, CMC 4 and CMC 5 as well as certain animal-by-product–derived materials must be hygienised, and the finished RNF must comply with the Annex I endpoints corresponding to its PFC. Products without biodegradable organic matter, such as most inorganic fertilisers, are normally exempt, unless they contain more than 1 % organic carbon from specified sources. For PFC 7 the most stringent included requirement applies. The mapping of relevant PFC to Annex I endpoints and compliant processes is summarised in Table 3.

Recognised process options and the corresponding pathogen limits are given in Table 3. For CMC 3 validated time–temperature profiles (≥ 70 °C × 3 d; ≥ 65 °C × 5 d; ≥ 60 °C × 7 d; or ≥ 55 °C × 14 d) are accepted. For CMC 4/5 anaerobic digestion must be combined with pasteurisation according to ABP rules or followed by composting. In all cases the finished RNF must meet the Annex I endpoints (see Table 3).

Table 3. Hygienisation requirements under Regulation (EU) 2019/1009 for PFC relevant to RNF

PFC	EU hygiene endpoint (Annex I)	Example compliant process (Annex II, CMC)
1(A)	*Salmonella* absent in 25 g; *E. coli*/Enterococcaceae ≤ 10^3 CFU g^{-1}; n = 5	CMC 3: ≥ 70 °C × 3 d / ≥ 65 °C × 5 d / ≥ 60 °C × 7 d / ≥ 55 °C × 14 d; CMC 4/5: AD + pasteurisation or AD + composting
1(B)	as 1(A)	if containing CMC 3/4/5, same profiles as above
1(C)*	as 1(A) (if > 1 % C_org)	hygienised CMC 3 or CMC 4/5 as above
3(A)	as 1(A)	CMC 3 meeting any profile above
4	as 1(A)	CMC 3 or CMC 4/5 treated as above
6(A)	broader pathogen panel; Enterococcaceae ≤ 10 CFU g^{-1}; n = 5	controlled production ensuring Annex I endpoints; no fixed heat step

PFC	EU hygiene endpoint (Annex I)	Example compliant process (Annex II, CMC)
6(B)	as 1(A)	any validated process achieving Annex I endpoints

AD = anaerobic digestion; ABP = pasteurisation under Animal By-Products rules. Endpoints apply to the finished product; listed processes are examples recognised through CMC.

National Variations of Hygienisation requirements of RNFs

Although Regulation (EU) 2019/1009 sets harmonised microbiological safety thresholds for fertilising products, several Baltic Sea Region countries apply additional or more specific hygienisation rules. **Germany** enforces stricter requirements through its Fertiliser Ordinance (DüMV) and Bio-waste Ordinance (BioAbfV), mandating validated sanitisation processes such as pasteurisation or high-temperature composting to ensure pathogen elimination. **Poland** also goes beyond EU standards by requiring that organic and organo-mineral fertilisers, as well as soil improvers, are completely free from Salmonella and parasitic eggs (e.g., Ascaris spp., Toxocara spp., Trichuris spp.). **Estonia** prescribes compliance with EC Regulation No 142/2011 for products containing digestion residues or compost and sets explicit microbiological limits, including the absence of Salmonella in 25 g and E. coli below 1,000 CFU/g. **Sweden** supplements EU-wide microbiological standards by enforcing specific thermal regimes for composting: at least 55 °C for 2 weeks or 65 °C for 1 week, particularly for materials containing animal by-products. Facilities processing such materials must also be approved and registered with the Swedish Board of Agriculture. These national measures reflect a shared objective of safeguarding public and environmental health, while introducing additional verification steps beyond the EU baseline.

6 Nutrient Requirements for Evaluating RNF

Nutrient requirements form the core of evaluating RNF, since they determine the agronomic value, environmental safety and compliance with EU standards. Minimum thresholds for macronutrients, micronutrients, organic carbon (C_org) and dry matter (DM) ensure that RNF deliver a tangible fertilising effect while avoiding the circulation of products with marginal nutrient content. These requirements also provide a harmonised basis for declaration and labelling, enabling consistent assessment across markets and regulatory frameworks in the Baltic Sea Region.

The EU regulation specifies PFC-specific minima that must be met for a product to qualify as a fertiliser, soil improver or related category. For fertilisers under PFC 1(A) and PFC 1(B), declared nutrients must reach defined concentrations of N, P_2O_5 or K_2O, with additional conditions for organic N and minimum C_{org} content. PFC 1(C)(I) requires higher compound nutrient levels, reflecting the concentrated nature of mineral products, while PFC 1(C)(II) specifies thresholds for individual micronutrients and chelated forms. Soil improvers under PFC 3(A) must primarily provide organic matter rather than nutrients, with clear C_{org} and DM minima. For PFC 4–6, the focus shifts towards solubility, product information and labelling, since these categories are not primarily nutrient suppliers.

Table 4 summarises the required nutrient declarations and organic carbon thresholds for the relevant PFC.

Table 4. Minimum declared nutrient and organic carbon contents by PFC (EU Reg. 2019/1009)

PFC	Minimum declared nutrient contents	Min. sum of declared nutrients	Min. C_{org} / DM
1(A) solid	One primary: N ≥ 2.5% or P_2O_5 ≥ 2% or K_2O ≥ 2%. If >1: each ≥ 1%.	≥ 4%	≥ 15%
1(A) liquid	One primary: N ≥ 2% or P_2O_5 ≥ 1% or K_2O ≥ 2%. If >1: each ≥ 1%.	≥ 3%	≥ 5%
1(B) solid	One primary: N ≥ 2.5% (≥ 1% organic-N), or P_2O_5 ≥ 2% or K_2O ≥ 2%. If >1: N ≥ 2% (≥ 0.5% organic-N) and/or P_2O_5 ≥ 2% / K_2O ≥ 2%.	≥ 8%	≥ 7.5%
1(B) liquid	One primary: N ≥ 2% (≥ 0.5% organic-N), or P_2O_5 ≥ 2% or K_2O ≥ 2%. If >1: same per-nutrient minima.	≥ 6%	≥ 3%
1(C)(I) solid	Compound: N/P_2O_5/K_2O ≥ 3% each; MgO/CaO/SO_3 ≥ 1.5%; Na_2O ≥ 1%.	≥ 18%	—
1(C)(I) liquid	Compound: N/P_2O_5/K_2O ≥ 1.5% each; MgO/CaO/SO_3 ≥ 0.75%; Na_2O ≥ 0.5%.	≥ 7%	—
1(C)(II) straight	Typology minima: salts/oxides/hydroxides ≥ 10% micronutrient; micronutrient-based ≥ 5%; solutions/suspensions ≥ 2%.	—	—
1(C)(II) compound	Per-element minima (e.g. Fe 2% or 0.3% chelated; Zn 0.5% or 0.1% chelated).	≥ 5% (solid) / ≥ 2% (liquid)	—
3(A)	No nutrient minima; declare N/P_2O_5/K_2O if > 0.5% each.	—	≥ 7.5% and ≥ 20% DM
4	No nutrient minima; declare CAT-soluble N > 150 mg/L, P_2O_5 > 20 mg/L, K_2O > 150 mg/L; plus pH, EC, quantity.	—	—
5 / 6	No nutrient minima; labelling rules apply (composition for PFC 5; product and use info for PFC 6).	—	—

DM = dry matter; C_{org} = organic carbon; EC = electrical conductivity; CAT = calcium–acetate–lactate soluble fraction; "chelated" refers to micronutrients bound in chelated form (e.g. EDTA, DTPA).

By setting these thresholds, the regulation ensures that RNF are not marketed as fertilisers without providing real nutrient value. This is particularly important for organic formulations, where high moisture or low nutrient density could otherwise undermine agronomic effectiveness. At the same time, the requirements safeguard environmental performance by ensuring that nutrient application is predictable, declared and auditable.

National Variations of Nutrient Requirements for RNFs

While the EU Fertilising Products Regulation (2019/1009) provides harmonised nutrient thresholds, several Baltic Sea Region countries apply additional specifications or adjustments.

Germany's Fertiliser Ordinance (DüMV) sets lower minimum nutrient thresholds for solid organic fertilisers compared to the EU baseline. Products under PFC 1(A) must contain at least 1.5% nitrogen, 0.5% phosphorus (P_2O_5), or 2% potassium (K_2O), with a minimum organic matter content of 30% (dry matter basis). **Estonia** requires organo-mineral complex fertilisers to meet combined nutrient content rules: at least 1% N, 1% P_2O_5, and 1% K_2O, with the sum of these nutrients reaching 10% (N + P_2O_5 + K_2O) or specific combinations such as 10% (N + K_2O) or 8% (N + P_2O_5). These values must be expressed in water-soluble form, ensuring immediate plant availability. The regulation applies to fertilisers produced by chemical processes or mixing that include animal or plant tissues. **Finland** implements its nutrient requirements through the Fertilizer Act (711/2022) and the Decree on Fertilizer Products (964/2023), which are aligned with EU Regulation 2019/1009 but allow slightly lower thresholds for certain categories. Key provisions include: a) Solid organic fertilisers (PFC 1(A)): Must contain at least 1% of N, P_2O_5, or K_2O, with a combined minimum of 2% (m/m), and an organic carbon content of ≥10% (dry matter basis). b) Organo-mineral fertilisers (PFC 1(B)): Must contain at least 1% of N, P_2O_5, or K_2O, with a combined minimum of 7% (m/m) for solids and 5% (m/m) for liquids. c) Single-nutrient inorganic macronutrient fertilisers: Must contain at least 3% of N, P_2O_5, or K_2O, and sodium (Na) concentration must be <30%. d) Compound inorganic macronutrient fertilisers: Must include at least 1% of two primary nutrients (N, P, K), with a combined minimum of 7% (m/m) e) Liming materials (PFC 2): Must have a minimum neutralising value of 10% as Ca. f) Solid organic soil improvers (PFC 3(A)): Must have ≥15% dry matter and ≥7.5% organic carbon (m/m). g) Liquid organic soil improvers: Must have ≥2% organic carbon (m/m) or a combined nutrient content of ≥0.2% (m/m). h) Inorganic soil improvers: Must contain <7.5% organic carbon. Additionally, Finland enforces variation limits for declared nutrient contents: i) For inorganic and organo-mineral fertilisers: ±25% or max 1–2 percentage units from the declared value. ii) For organic fertilisers and soil improvers: ±50% or max 1 percentage unit deviation is allowed. **Poland** enforces detailed nutrient requirements for different fertiliser types. Solid organic fertilisers must contain at least 0.3% N, 0.2% P_2O_5, and 0.2% K_2O, with an organic matter content of ≥30% (dry matter basis). Liquid organic fertilisers require 0.08% N, 0.05% P_2O_5, and 0.12% K_2O. Organo-mineral fertilisers have higher thresholds: solids must include 1% N, 0.5% P_2O_5, and 1% K_2O, with ≥20% organic matter, while liquids require 0.5% N, 0.2% P_2O_5, and 0.5% K_2O. These national rules ensure minimum agronomic value and product consistency. **Other countries**: Additional data can be also found for Denmark, Lithuania and Latvia.

7 Contaminants

Contaminant control is a central safety pillar for RNF under Regulation (EU) 2019/1009. EU fertilising products may only be placed on the market if their intended or reasonably foreseeable use does not pose a risk to human, animal or plant health, to safety, or to the environment. This principle is implemented through binding product requirements at PFC level and material-specific restrictions at CMC level. The most relevant contaminant groups in practice are (i) heavy metals and metalloids, (ii) organic contaminants, (iii) physical impurities and other impurity caps, and (iv) antibiotics (not regulated in EU).

7.1 Heavy metals and metalloids

Toxic elements such as arsenic, cadmium, mercury, nickel or lead require strict thresholds due to their persistence in soils, potential for long-term accumulation, and toxicity for plants, animals and humans. Within the EU framework, binding values are set at PFC level and must be respected by finished RNF; the full set of thresholds is given in Table 5.

Table 5. Heavy metal and metalloids thresholds limits by PFC (mg/kg dry matter unless noted; for 1(C)(II) see note) (EU Regulation 2019/1009)

PFC	Arsenic	Cadmium	Chromium VI	Mercury	Nickel	Lead	Copper	Zinc
1(A)	40	1.5	2	1	50	120	300	800
1(B)	40	3 or 60☆	2	1	50	120	600 †	1 500 †
1(C)(I)	40	3 or 60☆	2	1	100	120	600 †	1 500 †
1(C)(II)	1 000 ★	200 ★	—	100 ★	2 000 ★	600 ★	—	—
2	40	2	2	1	90	120	300	800
3(A)	40	2	2	1	50	120	300	800
3(B)	40	1.5	2	1	100	120	300	800
4	40	1.5	2	1	50	120	200	500
6	40	1.5	2	1	50	120	600	1 500

PFC = product function category; DM = dry matter.

★ For PFC 1(C)(II) the values are per kg of the sum of declared micronutrients

☆ For PFC 1(B) and 1(C)(I): 60 mg Cd per kg P_2O_5 when total P is at least 5 percent P_2O_5, otherwise 3 mg Cd per kg dry matter.

† Copper (Cu) and zinc (Zn) maxima in PFC 1(B) and 1(C)(I) do not apply when Cu or Zn is intentionally added as a micronutrient and declared according to Annex III

7.2 Organic contaminants

Organic contaminants are regulated at CMC level. The limits apply to the finished RNF whenever the respective recovered material is present. The most prominent group is polycyclic aromatic hydrocarbons (PAH_{16}), a set of hydrophobic, persistent compounds formed during incomplete combustion; they may enter RNF via soot-contaminated green waste, treated wood fractions, or thermochemical products processed under suboptimal conditions. Another regulated group are polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/F). The harmonised limits are summarised in Table 6; whenever the listed CMC occurs in a product, the corresponding limit applies.

Table 6. Organic contaminant limits at component level

CMC	Organic contaminant(s)	Limit	Basis	Applies at
3	PAH (sum of 16 EPA)	≤ 6 mg/kg	DM	Product

4	PAH (sum of 16 EPA)	≤ 6 mg/kg	DM	Product
5	PAH (sum of 16 EPA)	≤ 6 mg/kg	DM	Product
13	PAH (sum of 16 EPA)	≤ 6 mg/kg	DM	Product
13	PCDD/F	≤ 20 ng WHO TEQ/kg	DM	Product
13	PAH (sum of 16 EPA)	≤ 6 mg/kg	DM	Product
14	PCDD/F	≤ 20 ng WHO TEQ/kg	DM	Product
14	PAH (sum of 16 EPA)	≤ 6 mg/kg	DM	Product

CMC = component material category; PAH_{16} = sum of 16 EPA priority polycyclic aromatic hydrocarbons; PCDD/F = polychlorinated dibenzo-p-dioxins and dibenzofurans; WHO TEQ = World Health Organization toxic equivalents; DM = dry matter. “Applies at: Product” = limit applies to the finished fertilising product whenever the respective CMC is used.

7.3 Physical impurities and other product level impurity caps

Macroscopic impurities larger than 2 mm are restricted at CMC level for compost (CMC 3) and digestates (CMC 4 and 5). These values are carried forward into any RNF containing such inputs. The limits are presented in Table 7.

Table 7. Macroscopic impurities > 2 mm at CMC level

CMC	Impurity	Limit and basis	Notes
3	Glass, metal, plastics > 2 mm	Each ≤ 3 g/kg DM, sum ≤ 5 g/kg DM	Plastics within the sum ≤ 2.5 g/kg DM from 16 July 2026. Review foreseen by 16 July 2029
4	Glass, metal, plastics > 2 mm	Each ≤ 3 g/kg DM, sum ≤ 5 g/kg DM	Same staged plastic cap as CMC 3
5	Glass, metal, plastics > 2 mm	Each ≤ 3 g/kg DM, sum ≤ 5 g/kg dry matter	Same staged plastic cap as CMC 3
12	Organic matter, glass, stones, metal, plastics > 2 mm	Each ≤ 3 g/kg DM; sum ≤ 5 g/kg DM	No separate staged plastics sub-cap specified for CMC 12

CMC = component material category; DM = dry matter.

In addition to these CMC-based limits, a small set of impurity restrictions applies directly at PFC product level. These limits affect the finished RNF regardless of input material and are shown in Table 8.

Table 8. Product level impurity caps by PFC

PFC	Impurity or constituent	Limit or condition	Basis
All PFCs	Phosphonates	Must not be intentionally added. Unintentional presence ≤ 0.5 percent by mass	Product
1(A)	Biuret	Must not be present	—
1(B)	Biuret	≤ 12 g/kg	DM
1(C)(I)	Biuret	≤ 12 g/kg	DM
1(C)(I)	Perchlorate	≤ 50 mg/kg	DM

PFC = product function category; DM = dry matter.

These requirements ensure that RNF are not only chemically safe but also free from excessive macroscopic impurities or undesirable residues that could impair handling and application.

7.4 Antibiotics in RNFs

Antibiotic residues are an emerging concern for RNF, especially when derived from human or animal excreta. These compounds can survive common processing routes such as composting or anaerobic digestion, and their persistence raises two types of risks: direct disruption of soil microbial communities and indirect promotion of antimicrobial resistance (AMR). Both effects may undermine soil health, nutrient cycling and long-term agricultural productivity.

Current regulatory frameworks provide no explicit thresholds. Regulation (EU) 2019/1009 sets contaminant limits for heavy metals and certain organic pollutants, but antibiotics are not yet addressed. This regulatory gap reflects both methodological challenges, because antibiotics are a chemically diverse group with varying degradation pathways, and the limited availability of harmonised monitoring data across Member States.

Recent research emphasises that antibiotics in RNF should not be viewed solely as a chemical contaminant problem but as an ecological risk factor. Albert and Bloem (2023) stress that a combined assessment strategy is required, consisting of:

- **Chemical monitoring** to quantify antibiotic residues at relevant concentrations,
- **Ecotoxicological testing** to capture effects on microbial functioning, soil invertebrates, plants and aquatic organisms,
- **AMR risk evaluation** to track potential shifts in resistance gene pools in soil and water after RNF application.

Such an integrated approach provides a more comprehensive picture than chemical analysis alone, since the bioavailability and mixture effects of antibiotic residues often determine their ecological relevance. Ecotoxicological test batteries that are already applied in the context of bio-based fertilisers can be extended to cover antibiotic residues and their transformation products.

Although no binding limits currently exist, systematic monitoring of antibiotics in RNF is increasingly recommended, particularly for materials sourced from sewage sludge, manure or digestate with human or veterinary inputs. A consolidated overview of potential sources, risks, mitigation options and regulatory status is given in Table 9.

Table 9. Antibiotics in RNF: potential sources, risks, mitigation options and regulatory status

Source of antibiotics in RNF	Potential risks	Mitigation options	Regulatory status (EU)
Animal manure, slurry, digestate (CMC 4, CMC 5)	Persistence of antibiotic residues; alteration of soil microbiota; promotion of AMR	Thermophilic composting; high-temperature or extended anaerobic digestion; advanced oxidation or combined treatment; controlled storage	No threshold values defined in Regulation (EU) 2019/1009; only voluntary or national schemes
Sewage sludge and derived products (CMC 13, CMC 14)	Accumulation of pharmaceuticals and metabolites in soil; potential uptake by crops; spread of AMR in soil and water systems	Advanced treatment technologies (ozonation, pyrolysis, hydrothermal carbonisation); hygienisation and strict process monitoring	No harmonised EU limits; partially addressed under wastewater and sludge directives, but not in FPR
Mixed organic waste streams	Uncontrolled antibiotic carry-over; diffuse soil contamination and AMR risk	Strict input control; separation of feedstocks; targeted monitoring and product testing	Not explicitly regulated; conformity depends on CMC compliance

RNF = recycled nutrient fertiliser; CMC = component material category; AMR = antimicrobial resistance; FPR = Fertilising Products Regulation (EU) 2019/1009.

8 Physical Properties of RNFs

The physical properties of RNFs are decisive for their suitability in agricultural practice, their usability in different application techniques, and their requirements regarding storage and transport. Along the entire supply chain from production to plant uptake, fertilisers are exposed to a series of technological steps. These include loading at the factory depot, transport to storage facilities, intermediate storage at the vendor's depot, further loading and transport to the farm, storage on the farm, subsequent loading for field transport, transfer into the spreader, distribution in the field, and finally incorporation into the soil. The last and crucial stage is the decomposition of the fertiliser in the soil, where physical, chemical, and biological processes determine the release and uptake of nutrients by plants. Technological measures aim to influence these final processes in an agronomically efficient and environmentally compatible way. During the technological stages of handling, fertilisers are exposed to variable environmental conditions. Relevant factors include fluctuations in temperature, air humidity, vibration, mechanical impact, pressure from overlying material or moving machine elements, frictional forces along transport paths, biological contact with microorganisms, insects, or rodents, as well as the influence of chemically aggressive substances, electromagnetic effects, and radiation such as light and ultraviolet exposure. Each of these factors can alter the structural integrity and performance of the product.

A number of particle-specific properties are decisive for the spreading quality and overall performance of RNFs. These include volumetric weight, particle size, particle density, bulk density, particle shape, compression durability, flowability, surface-to-volume ratio, coefficient of friction, hygroscopicity, solubility, and mechanical resistance. The more uniform these properties are across the product, the more uniform is the distribution of nutrients per unit area in the field. For broadcast spreading, very small and light particles can be disadvantageous, as their flight distance is strongly reduced by air resistance and they are more easily affected by wind drift. Conversely, excessively large or non-uniform particles can cause segregation and uneven nutrient application. Uniform particle size and density help to prevent segregation during handling. Fractionation processes, in which smaller or denser particles accumulate at the bottom of the hopper while larger or lighter particles remain at the top, reduce the precision of fertiliser application. Equally important is the mechanical stability of the particles: breakage during spreading alters flight trajectories and increases dust formation, both of which reduce spreading uniformity. Blended fertilisers are particularly sensitive to these effects because differences in physical properties between components promote segregation. In addition to particle integrity, dust formation, hygroscopicity, and surface quality of the granules influence both product safety and efficiency. Dust is a source of nutrient loss, environmental pollution, and occupational health risks, while hygroscopic behaviour can lead to clumping, caking, and changes in nutrient composition during storage. Coating technologies are therefore applied to protect the surface of granules, improve water resistance, and reduce dust formation. Flowability, friction, and surface-to-volume ratio further determine the ease of handling and the rate of nutrient release after application. For liquid RNFs and gels, viscosity, freezing temperature, and vaporization temperature represent additional critical properties. Viscosity governs the flow characteristics through pipes and nozzles, freezing temperature determines usability in cold climates, and vaporization temperature affects stability under heat exposure and the retention of volatile components. Together, these properties define not only the technical handling of RNFs but also their agronomic efficiency and environmental safety.

The following subsections describe the most important physical properties of RNFs in greater detail, including particle size and size distribution, particle and bulk density, particle shape, mechanical resistance, flowability, surface-to-volume ratio, surface quality, coefficient of friction, dust formation, hygroscopicity, solubility, granule hardness, viscosity, freezing temperature, and vaporization temperature. For each property, its influence on fertiliser performance, methods of measurement, and implications for practical application are outlined. The aim is to provide a systematic framework for quality assessment and to support the development of harmonized industry standards.

8.1 Particle characteristics

Particle size, density, bulk density, and shape jointly define the physical identity of RNFs. Particle size is of particular relevance because it directly determines spreading behaviour, dissolution dynamics, and nutrient uptake efficiency. Smaller particles expose a larger surface area, which accelerates solubility and nutrient release, while larger particles often allow a wider spreading width and may be favoured for controlled-release formulations. Since fertilisers always contain a range of particle sizes, particle size distribution is reported in addition to average parameters such as the median diameter (d_{50}). **Figure 1** illustrates how granule positioning changes when particle diameters differ threefold, even if the total particle volume remains constant.

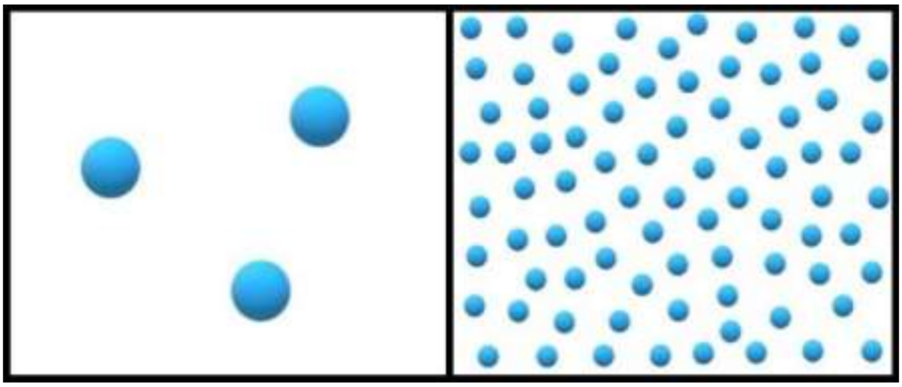

Figure 1. Position of the granules on the surface when the difference in diameter of the granules is three times but the sum of the volumes of the granules is the same. (Tamm and Vettik, 2023)

Several indices are commonly used to describe size and uniformity. The Size Guide Number (SGN) expresses mean particle size multiplied by 100, so that a fertiliser with a mean diameter of 1.5 mm corresponds to SGN = 150 (Fulton and Port 2016). The Granulometric Spread Index (GSI) quantifies particle size variability according to

$$GSI=\frac{d_{84}-d_{16}}{2\cdot d_{50}}\cdot 100$$

where d_{16}, d_{50} and d_{84} are the particle diameters at the 16th, 50th and 84th percentiles. Values below 15 indicate homogeneous particle size and good spreading uniformity. The Uniformity Index (UI) is another measure, defined as

$$UI=\frac{d_{95}}{d_{10}}\cdot 100$$

Particle density and bulk density influence flow behaviour and flight trajectories. High-density particles are less susceptible to wind drift and have longer flight paths, whereas variations in bulk density complicate calibration of volume-based spreading equipment. Bulk density is reported either as “loose” bulk density, determined when material is freely poured into a container, or as “packed” bulk density, measured after tapping until the volume stabilises (ISO-7837-1992).

The shape of granules further modifies spreading behaviour. Spherical particles roll easily across spreading discs and tend to exit at consistent angles, while irregularly shaped particles slide with higher friction, producing greater variation in exit velocity. Shape heterogeneity increases the risk of segregation, particularly in fertiliser blends. Although particle shape contributes to spreading performance, size variation generally exerts a stronger influence. When particle sizes or densities differ strongly within one mixture, segregation occurs in storage or during application. Figure 2 shows such fractionation, with small and dense granules accumulating in the lower part of the hopper, while larger particles remain on top.

Figure 2. Fractionation of the fertiliser mixture in the fertiliser box (BASF-Effizient fertiliser, 2012).

8.2 Mechanical stability

Mechanical stability encompasses both the resistance of particles to external stress and their intrinsic hardness. It determines whether fertilisers can withstand transport, loading, and spreading without excessive breakage. Granules with insufficient resistance disintegrate during handling, increasing dust formation and producing fragments that alter flight trajectories, thereby reducing spreading uniformity. Compressive strength, typically measured in newtons per granule, quantifies the resistance of particles to breakage (IDFC 1986). Field assessments, such as crushing tests between fingers, provide rapid estimates of granule hardness and can be used to adapt disc rotation speeds: fragile particles require speeds below 700 min^{-1}, medium-strength particles between 700 and 800 min^{-1}, and strong granules can withstand speeds above 800 min^{-1} (Fulton and Port 2016).

8.3 Surface-related properties

The surface of fertiliser granules strongly affects stability and nutrient release. The surface-to-volume ratio (SA:V) determines how quickly nutrients are mobilised. A high ratio accelerates dissolution, whereas a low ratio delays nutrient availability and is advantageous in controlled-release fertilisers (Fulton and Port 2016).

Surface coatings improve mechanical resistance and reduce water uptake, thereby preventing caking and excessive dust formation. Pigments are often incorporated to facilitate product identification and quality control.

Hygroscopicity is defined as the ability of particles to absorb or release moisture depending on ambient humidity. The critical relative humidity (CRH) marks the threshold at which moisture uptake increases sharply, a value that decreases with increasing temperature. Above CRH, granules may soften, swell, or crack, which reduces particle strength, promotes dust formation, and increases the risk of equipment clogging. To counteract these processes, surface treatments containing surfactants and powders are applied to control crystallisation and reduce contact surfaces (Carlson and Le Capitaine 2022).

8.4 Solubility and dissolution

Solubility determines the rate at which fertilisers dissolve in soil water and thus the timing of nutrient availability. Products with high solubility provide rapid nutrient release but may suffer from leaching losses, while products with lower solubility extend the period of nutrient supply. Solubility is influenced by particle size, surface-to-volume ratio, and coating technology (Carlson and Le Capitaine 2022). The deliberate adjustment of solubility through physical modification is a central principle in the development of slow- and controlled-release RNFs.

8.5 Properties of liquid fertilisers

Liquid RNFs and gels exhibit physical properties that are not relevant for solids but are essential for their storage and application. Viscosity defines flow behaviour through pumps, pipes, and nozzles. Low viscosity ensures smooth application but may reduce adhesion to plant surfaces, while high viscosity improves adherence but can increase clogging risks (Prevention 2006).

Freezing temperature is critical in temperate and cold climates. Fertilisers with a low freezing point remain usable under early-spring conditions, whereas products with higher freezing points require controlled storage.

Vaporisation temperature determines the stability of liquid RNFs under thermal stress. Products with low vaporisation points lose volatile components, reducing nutrient efficiency and contributing to emissions. Formulations with higher vaporisation points are more stable and ensure effective nutrient delivery, especially in foliar and fertigation applications (Carlson and Le Capitaine 2022).

8.6 Handling and flow behaviour

The ability of fertilisers to flow uniformly through storage, transport, and application equipment is determined by flowability, friction, and dust generation. Good flowability ensures consistent dosing, prevents blockages, and reduces segregation. Poor flowability is often linked to high humidity, which promotes adhesion and caking.

The coefficient of friction describes the resistance encountered when particles move against each other or along machine surfaces. A high coefficient increases contact time on spreading discs, alters exit angles, and can therefore impair uniformity (Fulton and Port 2016). Particle shape strongly affects friction, as angular particles exhibit higher resistance than spherical granules.

Dust formation occurs when fragile particles break during handling, transport, or spreading. It represents an economic loss through nutrient inefficiency, a health risk for workers, and an environmental pollutant. Figure 3 shows dust clouds generated during spreading of weak fertiliser granules, underlining the agronomic and occupational relevance of this property. Excessive dust is particularly problematic in fertilisers with low mechanical resistance, poor surface structure, or hygroscopic behaviour, and in systems using worn equipment (Hignett 1985).

Figure 3. Generation of excessive dust during the spreading of mechanically weak fertiliser granules using a field spreader (Photo by Tamm, Kalvi , 2023).

9 Practical use of RNFs

Recycled Nutrient Fertilisers (RNFs) are becoming an essential component of sustainable nutrient management. Their practical use depends on parameters that influence efficiency, usability, and environmental compatibility. Both solid RNFs (pelleted, granulated, powdered, or loose) and liquid RNFs (solutions, suspensions, slurries) must be considered equally, as their physical form determines requirements for storage, transport, and application technology.

In Sweden, pelleted digestate from municipal biowaste has shown good nutrient performance but faced challenges with dust formation during spreading, requiring equipment adjustments. In Finland, struvite recovered from wastewater treatment has been successfully used in precision placement systems, but its low solubility limits use in conventional broadcast spreading. Estonian farmers using composted manure reported clumping issues during storage in humid conditions, highlighting the need for improved drying and packaging. These examples illustrate the importance of matching RNF physical properties with farm-level logistics and technology.

9.1 Storability

Storability is critical to maintaining the quality of RNFs from production to application.

- **Moisture content** is decisive: solid RNFs with >15% water are prone to microbial growth, clumping, and nutrient loss, while liquids require sealed containers to prevent microbial contamination and evaporation.
- **Physical form**: granulated and pelleted RNFs are more stable than powders or loose composts; coatings and drying processes improve resistance to caking and degradation.
- **Temperature and humidity**: both solid and liquid RNFs require cool, dry storage. Hygroscopic products (e.g. ammonium-based) need airtight containers; liquids must be frost-protected and stabilized against stratification.
- **Shelf life**: dry and pelleted RNFs remain stable for 6–12 months or longer; liquids may degrade faster through microbial activity unless stabilised. Stock rotation (“first in, first out”) is recommended.

9.2 Transportability

Transportability determines economic viability and safety:

- **Bulk density and volume**: compact RNFs (granules, pellets) are cost-efficient to transport, whereas loose composts or slurries increase volume and logistics costs.
- **Packaging**: solid RNFs require moisture-resistant bags or big-bags; liquids demand sealed, corrosion-resistant tanks.
- **Handling**: pellets and granules can be conveyed with standard equipment; powders often need special dust control; liquids require pumps and hoses adapted to viscosity.
- **Regulatory aspects**: some RNFs (especially waste-derived) may fall under transport of dangerous goods; compliance with local and international legislation is mandatory.

9.3 Application techniques

Application efficiency depends on adapting RNFs to existing technology:

- **Solid RNFs**:
    - *Broadcast spreading* with centrifugal disc or boom spreaders is suitable for granules, pellets, and powders (lime spreaders).
    - *Soil incorporation* (ploughing, harrowing) improves nutrient retention and reduces volatilization.
    - *Precision placement* (banding, strip-till) increases nutrient-use efficiency, especially for low-solubility products such as struvite.
    - QA requires attention to particle size distribution (D <2 mm, 2–3.3 mm, 3.3–4.75 mm, >4.75 mm), density (~1 kg L^{-1}), strength (>3–10 kg), and flowability (~10 L min^{-1}).
- **Liquid RNFs**:
    - *Spraying* with crop sprayers is standard for liquid N and can be extended to liquid RNFs if particle-free.
    - *Fertigation* delivers RNFs through irrigation systems, requiring high solubility and low clogging risk.
    - *Slurry application* with manure spreaders is feasible for less concentrated RNFs, provided even distribution is ensured.

Farmers may perform simple tests (e.g. sieving, density measurement, flow rate) to adjust equipment settings. Collaboration between RNF producers and spreader manufacturers is essential to ensure compatibility and to provide setting recommendations.

10 Quality assurance

Ensuring the quality of RNFs is critical to their agronomic performance, safety, environmental compliance, and market acceptance. A structured quality assurance (QA) framework must integrate criteria related to hygienisation, stability, nutrient availability, contaminant control, and physical quality. This enables evaluation not only of the declared nutrient content, but also of a product's safety, usability, and long-term reliability.

From a QA standpoint, RNFs must be hygienically safe and free from pathogens, ensuring **biosecurity** in their production and use. Stability is another critical criteria, metrics like oxygen uptake rate and residual biogas potential demonstrate that RNFs remain microbially inert during storage and transport, minimizing odour formation, heating, or nutrient loss and ensuring that the product stays effective until application.

Agronomic safety is equally important. Improperly processed or immature RNFs can immobilise nitrogen, release harmful compounds, or exhibit unpredictable nutrient release rates. Including parameters such as phosphorus solubility or nitrogen mineralisation indicators in QA ensures reliable plant nutrient availability.

Contaminant control forms a third QA dimension. RNFs must contain heavy metals and organic pollutants, such as PAHs, dioxins, or antibiotics, at levels well below critical thresholds. and should ideally be evaluated in relation to nutrient content. Concepts like Toxin Rating (TR) and Cumulative Toxin Rating (CTR) help transparently assess the balance between nutrient benefits and contaminant risks.

Finally, RNFs must be **physically and practically viable** under real farming conditions. Key properties include particle size, homogeneity, bulk density, flowability, low dust generation, and resistance to abrasion. These factors enable efficient handling, uniform application with standard machinery, and higher farmer acceptance.

Together, these QA dimensions align with the Annex I & II of Regulation (EU) 2019/1009 for CE marking, forming a robust framework that ensures RNFs are safe, effective and competitive as sustainable alternatives to mineral fertilisers.

10.1 Hygienisation and Stability – Quality Assurance Dimension

Hygienisation and stability are core requirements in the quality assurance of RNFs, particularly for those derived from biodegradable organic materials (compost, digestates, biowaste, sewage sludge products). They ensure that products are safe for human, animal and plant health, can be stored without risk, and meet the standards for CE-marking under Regulation (EU) 2019/1009.

10.1.1 Hygienisation

The purpose of hygienisation (H) is the elimination of pathogens such as Salmonella spp., Escherichia coli and helminth eggs. EU Regulation 2019/1009 Annex I specifies microbiological safety thresholds:

$$H=\begin{cases} 0 \text{ if Salmonella spp. detected in 25 g sample} \\ \le 10^{3} \text{ CFU g}^{-1} \text{ E.coli} \end{cases}$$

These thresholds ensure that RNFs do not pose sanitary risks when applied to agricultural soils.

Process routes (CMC-specific):

- **Composting:** sufficient time–temperature profiles (e.g. ≥55 °C for ≥2 weeks, with turning).
- **Anaerobic digestion with pasteurisation:** e.g. ≥70 °C for 1 h or equivalent.

- **Thermal treatment (ash, biochar):** pathogens destroyed by high-temperature incineration or pyrolysis.

Testing is performed by microbiological assays on representative samples. CMC 12 (precipitated phosphate salts and derivatives) also includes recognised process routes under Annex II of Regulation (EU) 2019/1009. These routes typically involve precipitation from wastewater or process streams, followed by controlled separation and drying steps to ensure compliance with hygienisation and contaminant safety requirements.

10.1.2 Stability

Stability prevents uncontrolled microbial degradation during storage and use, which could lead to odour, heating, phytotoxic compounds and loss of nutrients. Two key indicators are defined:

- **Oxygen Uptake Rate (OUR):** $OUR \leq 25$ mmol O_2 kg^{-1} OMh^{-1}

This parameter measures the microbial oxygen consumption per unit of organic matter (OM). OM refers to the combustible fraction of the dry matter (i.e. carbon-rich materials such as cellulose, lignin, proteins and fats). A low OUR indicates that the readily degradable organic matter has been largely stabilised.

- **Residual Biogas Potential (BMP):** $BMP \leq 0.25$ L $g^{-1}VS$

This parameter quantifies the amount of biogas (mainly methane and CO_2) still producible under anaerobic conditions per gram of volatile solids (VS). VS represents the fraction of DM lost upon ignition at 550 °C, i.e. the organic fraction that can be decomposed biologically. A low BMP shows that little biodegradable substrate remains.

10.2 Nutrient Availability – Quality Assurance (QA) Dimension

Nutrient availability is a central quality parameter for RNF because it directly determines their agronomic performance and compliance with regulatory nutrient declarations. In QA, nutrient availability describes the proportion of declared nutrient content that is accessible to plants under field conditions. It is measured with standardised solubility and extraction methods that ensure comparability between batches, products and product categories.

For **phosphorus (P)**, QA relies on water and citrate solubility tests. The nutrient availability index

$$NA_P = \frac{P_{H2O} + P_{citrate}}{P_{total}} \cdot 100$$

where:

P_{H2O} = water-soluble phosphorus,

$P_{citrate}$ = citrate-soluble phosphorus,

P_{total} = total phosphorus content.

distinguishes between immediately available fractions and those that act as slow-release sources. A high NAP indicates rapid nutrient supply, while a lower value dominated by citrate-soluble P reflects more gradual availability. This information is essential for batch documentation and particularly relevant for ash-based RNF and struvite.

For **nitrogen (N)**, QA focuses on the distribution between ammonium (NH_4^+-N), nitrate (NO_3^--N) and organic fractions (with $N_{mineralised}$ estimated via incubation tests or standard mineralisation coefficients). The index:

$$NA_N = \frac{N_{NH4} + N_{NO3} + N_{mineralised}}{N_{total}} \cdot 100$$

summarises immediate plant-available forms and the portion expected from mineralisation. Here, QA not only records nutrient levels but also evaluates the release dynamics, which must correspond to the intended use of the fertiliser.

Potassium (K) in RNFs is usually present as soluble salts (KCl, K_2SO_4). It is almost completely water-soluble:

$$NA_K \approx \frac{K_{H2O}}{K_{total}} \cdot 100 \ \approx 100\%$$

Thus, quality assurance focuses less on solubility and more on avoiding chloride-sensitive crops (e.g. potatoes, grapes) and ensuring homogeneous distribution.

For **magnesium (Mg) and sulphur (S)**, availability depends on mineral form and requires extractability tests (citric acid for Mg, sulphate analysis and incubation tests for S). The QA index:

$$NA_{MG/S} = \frac{X_{H2O} + X_{extractable}}{X_{total}} \cdot 100$$

(where X represents Mg or S) ensures that both soluble and slowly available pools are systematically monitored.

For **micronutrients (Fe, Mn, Zn, Cu, B, Mo)**, QA is based on extractants such as DTPA that simulate root uptake. The index

$$NA_{micro} = \frac{M_{extractable}}{M_{total}} \cdot 100$$

provides a harmonised way to compare availability across different RNF and under varying soil pH conditions.

In summary, nutrient availability in QA ensures that RNF deliver their declared nutrients in both form and quantity. It provides the scientific basis for labelling, supports CE conformity, and enables farmers to use RNF with predictable agronomic effects. The relevant nutrient fractions, test methods and QA implications are summarised in Table 10.

Table 10. Nutrient Availability in RNFs

Nutrient	Form of Occurrence	Test Method	Relevance for QA
Phosphorus (P)	Water-soluble P, citrate-soluble P (struvite, ash-based P)	Water and citrate solubility tests	Differentiates immediate vs. slow-release P; critical for struvite/ash-based RNFs
Nitrogen (N)	Ammonium (NH4+), nitrate (NO3-), organic N (mineralisable)	Mineral N analysis; incubation tests for mineralisation	Balance between quick availability and risk of losses; C/N ratio important

Nutrient	Form of Occurrence	Test Method	Relevance for QA
Potassium (K)	KCl, K2SO4 (salts, almost fully water-soluble)	Water solubility (almost 100%)	Fully available; focus on chloride sensitivity of crops and distribution uniformity
Magnesium (Mg)	Mg-phosphates, Mg-carbonates (partly soluble)	Citric acid or acid-extractable Mg tests	Availability depends on mineral form and solubility
Sulphur (S)	Sulphate-S (soluble), organically bound S (mineralisable)	Water solubility for SO4-S; incubation/mineralisation tests for organic S	SO4-S immediately available; organic S requires microbial mineralisation
Micronutrients (Fe, Mn, Zn, Cu, B, Mo)	Various oxides, chelates or organically bound forms	DTPA or other standard extractants (element-specific)	pH-dependent; extractability reflects agronomic effectiveness

QA = Quality assurance

10.3 Contaminants and Evaluation of RNFs in Relation to Nutrient Contents

Contaminant control is a central dimension of quality assurance (QA) for RNFs. To ensure agronomic effectiveness and environmental safety, RNFs must be evaluated not only with respect to their absolute nutrient and contaminant contents but also by assessing the relationship between beneficial and harmful components. This dual perspective allows for a balanced risk–benefit assessment and provides a scientific basis for regulatory compliance and industry standards.

10.3.1 Heavy Metals and Metalloids

Elements such as cadmium (Cd), lead (Pb), mercury (Hg), nickel (Ni), copper (Cu), zinc (Zn), and arsenic (As) are among the most strictly regulated contaminants in RNFs due to their persistence and toxicity. Excessive concentrations can impair plant uptake, soil microbial functions, and food chain safety. Regulation (EU) 2019/1009 sets maximum permissible limits depending on the product function category (PFC).

Relative risk is expressed by the Toxin Rating (TR):

$$TR_{\text{Heavy Metals/Metalloids}} = \frac{\text{Total Heavy Metal/Metalloid Load (mg/kg)}}{\text{Available Nutrient Content (g/kg)}}$$

This ratio ensures that contaminant concentrations are evaluated in the context of available nutrient value.

10.3.2 Organic Contaminants

Persistent organic pollutants (POPs) such as PAH_{16}, PCBs, and dioxins/furans represent a long-term risk due to their bioaccumulation potential. EU thresholds exist for specific RNFs (e.g. $PAH_{16} \leq 6$ mg kg^{-1} DM in composts and digestates). Their evaluation follows the same principle:

The TR for organic contaminants can be calculated using a similar formula:

$$TR_{\text{Organic Contaminants}} = \frac{\text{Total POP Load (mg/kg)}}{\text{Available Nutrient Content (g/kg)}}$$

10.3.3 Antibiotics

RNFs derived from manure or sewage sludge may contain antibiotic residues that can disturb soil microbial communities and contribute to antimicrobial resistance (AMR). While harmonised thresholds are not yet established, their impact can be evaluated using the same normalisation approach:

$$TR_{Antibiotics} = \frac{\text{Total Antibiotic Load (mg/kg)}}{\text{Available Nutrient Content (g/kg)}}$$

10.3.4 Physical Impurities

Glass, metal, and plastic fragments >2 mm do not directly affect nutrient dynamics but compromise usability and environmental integrity. Their impact is assessed as:

$$TR_{Impurities} = \frac{\text{Total Impurities Load (g/kg)}}{\text{Available Nutrient Content (g/kg)}}$$

10.3.5 Comprehensive Contaminant Evaluation

To provide an overall safety assessment, a weighted cumulative Toxin Rating (CTR) can be calculated:

$$CTR = \sum_{i=1}^{n} \omega_i \cdot TR_i$$

Where:

ω_i= weight factor for the importance of each contaminant type.

TR_i= Toxin Rating for each contaminant.

This approach allows for a balanced evaluation of multiple contaminant types in relation to their nutrient content.

10.4 Physical and Practical Quality of RNFs

The physical and practical quality of RNFs determines whether nutrients declared on the label can be delivered effectively under real agricultural conditions. Beyond chemical composition and contaminant thresholds, RNFs must demonstrate properties that allow **for safe storage, efficient transport, and reliable application** with standard agricultural equipment. These factors directly influence farmer acceptance and the competitiveness of RNFs in comparison to mineral fertilisers.

10.4.1 Storability

Storability ensures that RNFs maintain nutrient stability and physical integrity until use. Critical factors include moisture content, physical form, temperature and humidity tolerance, and shelf life. Granulated or pelleted RNFs are generally more stable than powders or untreated materials, while sealed packaging and proper storage conditions minimise microbial growth, clumping, or nutrient losses.

10.4.2 Transportability

Transportability defines whether RNFs can be moved cost-effectively and without degradation. Bulk density, packaging integrity, and ease of handling are key aspects. High-density, pelletised

RNFs reduce transport costs and can be loaded with standard equipment, while adequate packaging prevents nutrient losses and contamination. Compliance with transport regulations for waste-derived RNFs must also be documented as part of QA.

10.4.3 Applicability

Applicability describes the adaptation of RNFs to existing fertiliser application technology. To ensure uniform spreading, RNFs must meet criteria for particle size distribution, density, strength, flowability, and dust formation. Compatibility with centrifugal spreaders, seed drills, lime spreaders, or sprayers is critical. QA should therefore include both laboratory measurements and field spreading trials to confirm practical usability.

The integration of physical and practical indicators into QA guarantees that RNFs are not only chemically compliant but also technically usable. Storability prevents degradation, transportability ensures distribution efficiency, and applicability secures precise nutrient delivery. Together, these factors link product integrity with on-farm performance and are summarised in Table 11.

Table 11. Physical and practical quality indicators for QA of RNF: storability, transportability and applicability

Dimension	Key Parameters	Evaluation / Test Method	QA Relevance
Storability	Moisture content, physical form, temperature & humidity tolerance, shelf life	Moisture analysis; storage tests under controlled climate; packaging checks; stock rotation	Ensures nutrient stability, prevents microbial growth, clumping, or nutrient loss
Transportability	Bulk density, packaging integrity, handling properties, regulatory compliance	Density measurement; packaging durability tests; handling simulations; certification review	Guarantees cost-efficient distribution and maintains product quality during transit
Applicability	Particle size distribution, granule density & strength, flowability, dust formation	Sieve and density analysis; crushing strength; flow tests; dust chamber tests; field spreading trials	Secures uniform nutrient application and compatibility with existing farm machinery

QA = Quality assurance

11 Knowledge gaps and emerging concerns

Despite significant progress in the development of regulatory frameworks and treatment technologies, several knowledge gaps and emerging concerns remain with respect to the safe and sustainable use of RNF. These gaps relate both to scientific uncertainties and to differences in regulatory implementation within the Baltic Sea Region (BSR).

A major concern is the presence of **antibiotic residues** in RNF derived from human or animal excreta. Such residues can persist through processing and may affect soil microbial communities by promoting antimicrobial resistance (AMR). At present, Regulation (EU) 2019/1009 does not set threshold values for antibiotics. The potential risk to ecosystems and public health therefore requires systematic monitoring and the development of guidance for evaluation, combining chemical analysis, ecotoxicological testing and AMR risk assessment.

Another field of concern is **microplastics**, which can enter RNF through contaminated input materials such as sewage sludge or biowaste. Their long-term fate in soils, interactions with soil organisms and potential role as carriers of other pollutants are still poorly understood. Current regulation does not define threshold values for microplastics in RNF, which leaves a significant gap in quality assurance.

In addition, there is limited knowledge regarding **new substitute compounds**, for example alternative plasticisers, flame retardants or industrial additives, which may replace regulated substances but have similar or unknown environmental effects. Likewise, many substances used in agriculture or industry undergo **environmental transformation**, resulting in degradation products or intermediates whose persistence and toxicity can differ from the parent compounds. These transformation pathways and their long-term implications for soil and water quality are not yet well characterised.

The **combined and mixture effects** of multiple contaminants also remain insufficiently understood. Current regulatory practice generally assesses risks on a substance-by-substance basis, which may overlook important synergies or antagonisms in the soil environment. More research is needed to understand how such combined exposures influence crop safety, soil biodiversity and water quality.

Another knowledge gap concerns the **accumulation and persistence** of contaminants in soils. Factors such as temperature, moisture, pH, microbial activity and soil type strongly influence degradation rates, but quantitative data are limited. This makes it difficult to assess long-term risks or to define safe application rates for RNF in diverse farming systems.

Finally, a structural gap is the **regulatory heterogeneity within the EU Member States of the BSR**. While the EU Fertilising Products Regulation provides a common framework, several countries apply additional or stricter rules, for example for heavy metals, organic carbon or impurity thresholds. This uneven implementation creates uncertainty for producers and users, complicates cross-border trade, and hampers the establishment of harmonised QA standards in the region. Aligning national approaches more closely with the EU framework would help overcome these inconsistencies and support mutual recognition of RNF across the BSR.

Recent EU Horizon projects such as FERTIMANURE, NOMAD, and MINAGRIS have highlighted the presence and risks of microplastics in recycled fertilisers. Microplastics can originate from sewage sludge, composted biowaste, and packaging residues, and may persist in soils for decades. They can affect soil structure, water retention, and microbial communities, and may act as vectors for other pollutants. Emerging contaminants such as pharmaceutical residues, flame retardants, and industrial additives are increasingly detected in RNFs. These substances often lack regulatory thresholds and may undergo transformation into unknown by-products. EU projects recommend integrating advanced analytical techniques (e.g. LC-MS/MS, HRMS) and ecotoxicological assays to assess their impact. A harmonised monitoring framework is needed to address these risks and support future regulatory updates.

Together, these gaps demonstrate that while the EU regulation provides a solid foundation, further scientific, technical and regulatory work is required to ensure that RNF can be safely and confidently integrated into sustainable nutrient management strategies.

12 Conclusions

Quality assurance (QA) of recycled nutrient fertilisers (RNF) is essential for their acceptance as safe, effective and sustainable fertilising products in the Baltic Sea Region. The EU Fertilising Products Regulation provides a robust framework by defining clear criteria for nutrient content, hygienisation, stability, contaminant thresholds and physical usability. This common baseline enables RNF to enter the market under transparent and auditable conditions, fostering farmer confidence, regulatory oversight, and international trade.

However, several knowledge gaps and emerging risks remain. Issues such as antibiotic residues, microplastics, substitute chemicals, and transformation products are not yet fully addressed in regulatory practice. Moreover, the combined effects of multiple substances and the long-term accumulation of contaminants in soils are still poorly understood. Tackling these challenges requires targeted monitoring programmes, advanced analytical methods, and stronger integration of chemical testing with ecotoxicological assessment.

Another barrier is regulatory heterogeneity among EU Member States in the Baltic Sea Region. While the EU framework sets minimum requirements, national rules often impose stricter limits on heavy metals, organic carbon, or impurities. This uneven implementation hampers cross-border trade and complicates the development of uniform QA standards. Greater alignment with EU Regulation 2019/1009 would enhance mutual recognition of RNF and create more consistent conditions for producers and users.

Future QA frameworks should be built on the EU Regulation while progressively addressing emerging risks. Innovative approaches, such as the Toxin Rating, which relates contaminant loads to nutrient value, and integrated assessment schemes combining laboratory analyses with field performance tests offer promising tools for more contextualised evaluation. Practical parameters such as storability, transportability and on-farm applicability must also remain central, as they determine RNF reliability under real-world conditions.

If robust science, harmonised regulation, and practical usability converge, RNF can become a cornerstone of sustainable nutrient management. They hold the potential to reduce reliance on imported mineral fertilisers, close nutrient cycles, and support climate-neutral agriculture. Continuous improvement of QA standards, driven by scientific progress and stakeholder collaboration, will be key to realising this potential.

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This annex provides a structured quality assurance (QA) matrix for recycled nutrient fertilisers (RNFs). The purpose of the matrix is to operationalise the assessment scheme developed under Task 1.2 of the CiNURGi project. It translates the criteria described in the main body of the report into a practical tool that can be applied during product development, laboratory testing, and regulatory conformity assessment.

The matrix combines five main QA dimensions:

Hygienisation and stability – to guarantee product safety and biosecurity.

Nutrient availability – to ensure agronomic effectiveness and comparability across RNFs.

Contaminant control – to safeguard environmental quality and compliance with EU thresholds.

Physical and technical quality – to secure product integrity during storage, transport, and application.

Practical use and applicability – to confirm that RNFs are compatible with existing farm machinery and spreading technology.

Each row of the matrix specifies the QA dimension, relevant parameters, evaluation or test methods, and their significance for quality assurance. This approach allows producers, regulators, and end-users to check compliance systematically and to identify areas where additional monitoring or product optimisation is required.

The QA matrix is not intended as a replacement for legal requirements under Regulation (EU) 2019/1009 but as a complementary framework that highlights best practice in assessing RNF quality and safety. It may also serve as a reference for future harmonisation in the Baltic Sea Region and beyond.

Table A 1. Quality assurance matrix for recycled nutrient fertilisers (RNFs)

Dimension	Parameter	Test / Method	Threshold (EU 2019/1009 / national / suggested)	QA relevance	Notes
Hygienisation	Salmonella	EN ISO 6579, 0 in 25 g/ml		Ensures pathogen safety	Applies to all RNF with biodegradable OM
Hygienisation	E. coli / Enterococcaceae	Microbiological count, $\leq 10^3$ CFU g^{-1}/ml^{-1} (n=5)		Indicator for faecal contamination	Component- and product-level
Stability	Oxygen uptake rate (OUR)	Respirometric test	≤25 mmol O_2/kg OM/h	Prevents secondary fermentation	Compost, digestate
Stability	Residual biogas potential (BMP)	Anaerobic test	≤0.25 L biogas/g VS	Prevents gas formation	Digestate

Dimension	Parameter	Test / Method	Threshold (EU 2019/1009 / national / suggested)	QA relevance	Notes
Nutrient availability (P)	Water- & citrate-soluble P	EN 15958	% fractions declared	Differentiates immediate vs. slow release	Struvite, ash, compost
Nutrient availability (N)	NH_4^+, NO_3^-, organic N	EN 13654, incubation tests	Label & index values	Balances availability and loss risk	C/N ratio relevant
Nutrient availability (K)	Water solubility	EN 15958	≈100%	Fully available	QA focuses on crop sensitivity
Nutrient availability (Mg, S)	Acid-extractable Mg, sulphate-S	Citric acid test, water solubility	Label & index	Release depends on mineral form	
Nutrient availability (micros)	DTPA extractable Fe, Zn, Cu, Mn	DTPA extraction	Label & index	Reflects pH-dependent availability	
Contaminants	Heavy metals (Cd, Pb, Hg, Ni, Cu, Zn, As, Cr VI)	EN 13650, EN 16943	Thresholds by PFC (EU 2019/1009)	Long-term accumulation risk	Some stricter in BSR states
Contaminants	Organic (PAH16, PCDD/F)	GC/MS, HRGC/HRMS	PAH ≤6 mg/kg DM, PCDD/F ≤20 ng WHO-TEQ/kg DM	Persistent, bioaccumulative	CMC level
Contaminants	Antibiotics	LC-MS/MS	Not regulated	AMR risk	Monitoring recommended
Contaminants	Physical impurities	Visual/sieving	≤3 g/kg DM each, ≤5 g/kg DM sum	Prevents plastic/metal contamination	Plastics stricter from 2026
Physical / technical	Particle size distribution	Sieving, laser diffraction	UI 40–60, GSI <15	Spreading uniformity	
Physical / technical	Granule strength	Crushing force	≥3–10 kg	Prevents dust, ensures broadcast	
Physical / technical	Bulk density	ISO 7837	Declared & consistent	Calibration of spreaders	
Physical / technical	Dust index	Chamber test	DI <5%	Health, environment	
Practical	Storability	Moisture, climate tests	Moisture <15%, no secondary fermentation	Long shelf life	Depends on form
Practical	Transportability	Bulk density, packaging durability	Moisture-proof, mechanical stability	Maintains quality in transit	
Practical	Applicability	Field spreading tests	Compatible with centrifugal, seeders, sprayers	Ensures farmer adoption	Settings guidance needed

AMR = Antimicrobial Resistance, As = Arsenic, BMP = Biogas Potential (Residual), Cd = Cadmium, C/N ratio = Carbon-to-Nitrogen ratio, Cr VI = Hexavalent Chromium, Cu = Copper, DI = Dust Index, DM = Dry Matter, DTPA = Diethylenetriaminepentaacetic Acid (standard extractant for micronutrients), GC/MS = Gas Chromatography–Mass Spectrometry, GSI = Granulometric Spread Index, Hg = Mercury, HRGC/HRMS = High-Resolution Gas Chromatography/High-Resolution Mass Spectrometry, ISO / EN = International / European Standard test methods, LC-MS/MS = Liquid Chromatography–Tandem Mass Spectrometry, Ni = Nickel, OM = Organic Matter, OUR = Oxygen Uptake Rate, PAH16 = Sum of 16 polycyclic aromatic hydrocarbons (US EPA priority list), Pb = Lead, PCDD/F = Polychlorinated dibenzo-p-dioxins and dibenzofurans, QA = Quality Assurance, RNF = Recycled Nutrient Fertiliser, UI = Uniformity Index, VS = Volatile Solids, WHO-TEQ = World Health Organization Toxic Equivalents, Zn = Zinc

Draft Policy Brief

Towards Harmonised Quality Assurance for Recycled Nutrient Fertilisers (RNFs) in the Baltic Sea Region

Background

The sustainable management of nutrients is one of the key challenges for agriculture and the environment in the Baltic Sea Region (BSR). Excess nutrient losses contribute to eutrophication, greenhouse gas emissions, and soil degradation. At the same time, agriculture remains highly dependent on imported mineral fertilisers, often with high energy and climate costs.

Recycled Nutrient Fertilisers (RNFs) provide an opportunity to recover nitrogen, phosphorus, potassium, and organic carbon from waste streams, thereby reducing dependency on finite resources, lowering emissions, and contributing to the EU's circular economy and Farm to Fork Strategy. However, their acceptance in practice depends on **trust in quality, safety, and performance**.

The EU Fertilising Products Regulation (EU 2019/1009) provides a harmonised framework for CE-marked fertilisers, including provisions for nutrient content, hygienisation, stability, contaminants, and physical properties. Yet, within the BSR, national rules continue to differ. Some countries apply **stricter standards** (e.g. for heavy metals or organic carbon contents), while others retain **more flexible thresholds** for impurities or nutrient declaration. These variations hinder cross-border use of RNFs and complicate product development and marketing.

Challenges

1. **Heterogeneity of national frameworks**: Despite EU harmonisation, RNFs face different approval and quality requirements across the BSR. This increases administrative effort, reduces comparability, and discourages investment.
2. **Emerging contaminants**: While heavy metals, PAHs, and dioxins are regulated, substances such as antibiotics, microplastics, and transformation products remain outside binding limits. Their risks are recognised but not yet consistently addressed.
3. **Practical usability**: Farmers require RNFs that are not only safe and compliant but also storable, transportable, and compatible with existing spreading technology. Current QA frameworks do not fully integrate these technical aspects.
4. **Need for trust and acceptance**: Without transparent and comparable QA, RNFs risk being perceived as second-class fertilisers. This perception limits adoption despite environmental and policy benefits.

Key Messages

- **EU 2019/1009 is a strong baseline**: It defines core QA dimensions (hygienisation, stability, nutrient content, contaminants, impurities).
- **National deviations remain significant**: Stricter or looser rules exist for selected nutrients, impurities, or contaminants, reflecting local priorities but fragmenting the market. For RNFs with low nutrient content and high logistics costs per nutrient unit, a uniform harmonised QA that increases compliance effort can raise unit costs and effectively close otherwise viable national or regional markets.
- **A harmonised QA approach in the BSR is needed**: Voluntary adoption of EU 2019/1009 as a **common minimum platform** would ensure comparability and cross-border market access.
- **Best practice can complement harmonisation**: Stricter national criteria (e.g. lower Cd thresholds) can be recognised as additional requirements but should not undermine the EU baseline.
- **Harmonisation supports sustainability strategies**: Alignment across the BSR would strengthen the HELCOM Baltic Sea Regional Nutrient Recycling Strategy, the EU Green Deal, and national climate targets.
- **Proportionality matters**: A risk-based and size-sensitive QA is needed so that low-nutrient, bulky RNFs for short local supply chains are not priced out by one-size-fits-all conformity burdens.

Recommendations

1. **Adopt EU 2019/1009 as a common baseline** for all RNF QA in the BSR, ensuring that essential parameters (nutrient content, contaminants, hygienisation, impurities) are consistently applied.
2. **Promote voluntary harmonisation**: Even where national legislation diverges, stakeholders should agree to use the EU framework as a reference standard for evaluation, testing, and reporting.
3. **Implement the QA-Matrix developed in Task 1.2** as a practical tool for producers, researchers, and regulators. This matrix links criteria, test methods, thresholds, and open research gaps, providing a structured checklist for RNF evaluation.
4. **Validate the QA-Matrix in WP2** through laboratory analyses and field demonstrations across the BSR. These tests will confirm usability and highlight where further refinement is needed.
5. **Integrate findings into WP3 and Policy Briefs**: Engage with national authorities, farmer organisations, and HELCOM groups to promote convergence of standards.
6. **Address emerging contaminants**: Encourage research and monitoring of antibiotics, microplastics, and transformation products, with the aim of including them in future regulatory frameworks.
7. **Promote farmer acceptance**: Include storability, transportability, and applicability in QA checks to ensure that RNFs are practical and competitive alternatives to mineral fertilisers.

8. 8. Ensure proportional, risk-based QA implementation: Scale sampling frequencies and documentation to throughput and nutrient density, allow simplified conformity routes for short local supply chains, and use transitional arrangements to avoid unintended market exit of small producers.

Path Forward for Harmonisation in the BSR

- **Short term (WP2 validation)**: Apply QA-Matrix and Checklists to pilot RNFs. Collect comparable data on nutrient availability, contaminants, stability, and usability. Include pilots with low-nutrient, bulky RNFs to assess cost impacts of QA options and to calibrate proportional requirements.
- **Medium term (WP3 dialogue)**: Present harmonised QA results to regulators, certification bodies, and HELCOM to encourage voluntary adoption of EU criteria. Test simplified conformity routes for local markets and document their safeguards.
- **Long term (Policy alignment)**: Recommend that BSR states use EU 2019/1009 as the common QA platform, complemented by national best practices where justified. This would facilitate trade, foster innovation, and strengthen environmental protection. Embed periodic reviews to verify that QA requirements remain proportionate across product types and market scales.