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ORIGINAL ARTICLE

Nutrient recycling: from waste to crop

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Abstract
Within the transition to a bio-based economy from a fossil reserve-based world, we face the vital dare of closing nutrient cycles and moving to a more practical and balanced resource management, taking into account not only the economical but also the environmental perspective. The manufacture and transportation of mineral fertilizers are activities that require large amounts of fossil energy. Therefore, the dependence that agriculture has on fertilizers based on mineral reserves (mainly P, N, and K) should be considered as a very serious threat to human food security and climate change. On the other hand, the existing forecast on phosphorus reserves is pessimistic. According to the latest published figures on population growth and estimated demand for nutrients in the future, depletion of this material is expected to occur within a maximum of 300 years. At the same time, the agricultural demand that exists for mineral fertilizers is constantly growing. The main reason is the increase in the world population, together with the increase in meat consumption and the popularity of energy crops. Despite these negative perspectives, the processing or elimination of waste streams causes uncontrolled dispersion in the environment of a large amount of minerals. Thus, a new global effort is needed to draw a new scenario where improved nutrient use efficiency and, at the same time, reduced nutrient losses provide the bases for a more circular economy, to produce more necessary inputs, as food or energy, as the same time as decreasing environmental impact. This paper will show the process options which can "upcycle" and recover residual nutrients to high-quality end-products, defined by efficient nutrient use and will reveal the key issues to face with novel biofertilizer products and changing policies.

Keywords Circular economy · Nutrients cycle · Biofertilizers · Organic waste

1 Introduction

The world demand for total fertilizer nutrients (nitrogen, phosphorus, and potassium) is estimated to grow at 1.9% annually, reaching 202 million tons (expected) by the end of 2020 [1]. Figure 1 shows the nutrients balance situation foreseen for 2020 in different regions, calculated as the difference between fertilizer supply and demand.

The use of nutrients is not uniform. In developing countries, including sub-Saharan Africa and large areas of Latin America, only a minority of farmers use synthetic (commercial) fertilizers, while most produce at a subsistence level based on crop rotation and recycling of crop residues, animal excreta, and organic waste. On the other hand, throughout the developed world, and also in regions in rapid development as in East and South Asia, there is the problem of disproportionate use of nutrients which generates uncontrolled consequences.

When dealing with nutrients, there are four important aspects to consider according to Sutton et al. [2]: (1) In order to feed 7 billion people, the sustainability of this world depends on nutrients. Humans have almost tripled global land-based cycling of nitrogen (N) and phosphorus (P); (2) The cycles of N and P in the world are now unbalanced, producing significant environmental, economic, and health problems; (3) Limited access to nutrients still limits food production in some parts of the world and contributes to land degradation, while finite phosphorus reserves pose a real risk to future global food security, indicating the need for a controlled use; (4) Unless measures are taken, the increase in population, with the consequent increase in the consumption of animal products and energy, will exacerbate nutrient losses. This will result in increased pollution levels and land degradation,

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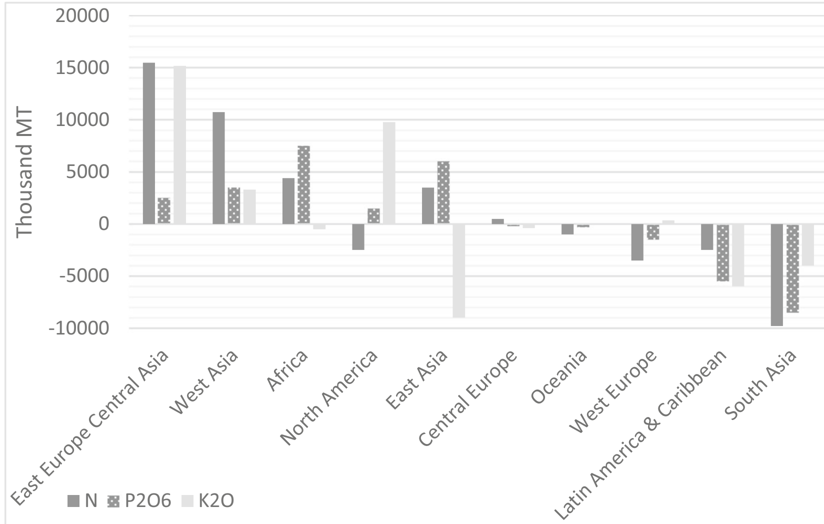

Fig. 1 Regional nutrients balance foreseen in 2020. Source: [1]

further affecting water, air, and soil quality, and will threat climate and biodiversity.

The imminent need in developed countries to replace the mineral nutrients that are part of synthetic fertilizers with nutrients derived from bio-based waste is evident. However, current technologies for the treatment of manure and biowaste are expensive and, often, their use is not specifically intended for mineral recovery. On the contrary, they focus on mitigating environmental effects, which often involve the elimination and general lack of use of these nutrients [3]. On the other hand, in developing countries, there is a need to improve access to affordable nutrients sources to limit the need for further conversion of land to crop production to maintain sufficient food supplies. This leads to the need for innovative models and better infrastructure to promote access to nutrients in cultivated areas generally far from fertilizer production and distribution centers. In parallel, efforts are needed to better perceive and face long-term sustainability risks, also considering synergies between imported mineral fertilizer sources, manure recycling, and biological nutrients fixation [4].

Recycling materials and energy through re-connecting crop and livestock production becomes indispensable for attaining agricultural sustainability in all the senses, not only in the environmental one. It is time to reconnect nutrient flows between crop production and livestock sectors. To do so, it is necessary to promote agro-industrial processes that favor the recycling of mineral nutrients contained in organic flows, to mineral fertilizers. This approach requires further development of a third agro-industrial pillar: processing and upcycling of agricultural waste. This pillar complements the two main existing pillars of agricultural activity such as crop and animal production [5].

2 Key actions to improve nutrient use efficiency

There are many options to improve nutrients management and avoid the typical problems associated with an inadequate production and use of fertilizers (natural or chemical). Working on improving nutrient use efficiency in crop and animal production is a good start point in the search of an increase in global food productions, making a rational and proportional use of external resources and minimizing environmental pollution due to these activities. This strategy, when applied specifically to crop production, is related to the implementation of five actions: (1) Implement the strategy “4R Nutrient Management Stewardship” whose base is to apply the right fertilizer, in the right amount, at the right time of application and in an appropriate way. This strategy has been developed specifically by the fertilizer industry according to the specific conditions of the land and considering the global availability of nutrients in soils, crop residues, manure, and waste [6]; (2) Select the most suitable crop according to the land where it is going to be planted and taking into account the season, all within a correct crop rotation; (3) Water the crop when necessary, using technology that allows controlling the amount of water added and the precise point of application, such as drip irrigation, combined with soil water collection methods and soil conservation practices; (4) Implement integrated measures to manage pests, weeds, and diseases to minimize yield losses while protecting the environment; (5) Reduce nutrient runoff through adequate mitigation actions that include initiatives for erosion control, tillage management, cover crops, and best practices for manure and fertilizer applications. These actions are aimed at advisers and farmers, but they must have the support of research communities and industry.

In reference to animal production, it has been traditionally focused around homes and done on a small scale. But with the increasing demand for animal products, such as milk, eggs, or meat, in the whole world, livestock has become an individual activity and animal production has turned more intense, particularly in countries that are highly developed. The result has been a concentration of the animal production systems. All activities in the value chain, such as production, processing, distribution, or marketing, have been more closely linked, particularly in the case of pig and poultry production. As a consequence, the number of animals per farm has increased, farms have professionalized, and manure production has grown, usually exceeding the limited capacity of nearby farmland to efficiently absorb and recycle their nutrients. This over-application of manure has exacerbated problems in vulnerable areas with nitrate leaching to groundwater, ammonia, and nitrous oxide releases to air and the collapse of soils with phosphorus to the term that phosphorus losses by leaching or through surface flow are serious concerns [7].

The strategy of improving nutrient use efficiency in animal production can be implemented following some approaches: (1) Genetic advances in livestock have allowed the animal to make a more efficient use of ingested feed and have a better assimilation of nutrients. As a consequence, the nutrient passes into meat, milk, or eggs instead of being excreted, considerably improving the productivity of animal feed. At the same time, improvements in animal housing and advances in veterinary medicine have resulted in healthier environments that also encourage better nutrient utilization and more efficient production of animal products [8]; (2) Avoid nutrient overfeeding and unnecessary enrichment of manure with valuable compounds. The use of easily digestible feeds, the adequate planning of animals diets, the establishment of nutritional requirements in the feeding, and the use of additives that increase the digestibility of nutrients in the feed are key measures to improve the efficiency of livestock in the assimilation of nutrients [9]; (3) Improve the fertilizer value of animal manure. This can be achieved by modifying animal diet (controlling the levels of nitrogen and phosphorus added), manure storage, and handling practices (avoiding losses to the environment) or improving fertilizer value by manure processing (pelletizing, mixing with inorganic fertilizer nutrients, extracting nutrients, etc.) [10].

Other strategies are focused on reducing nitrogen emissions in the form of NOx, N_2O, and NH_3 from transport and industrial activities, reducing CO_2 emissions simultaneously. According Garza-Reyes et al. [11], these include the set of techniques that reduce or capture nitrogen emissions in combustion processes, such as low NOx burners or catalytic reduction, use of techniques that improve combustion process through fuel efficiency, use of techniques that reduce energy requirement, or use of renewable energy, such as wind, solar, or geothermal energy.

In the group of key actions for waste and recycling, there are also several opportunities to optimize the management of nutrients. Most of them overlap for nitrogen and phosphorus, with the exception of operations related to phosphorus extraction (mining) and processing. Improving food supply efficiency and reducing food waste is one of these key actions. It is estimated that almost 90% of the world's consumption of phosphate rock is used to produce food and feed [12]. Since a large share of food is wasted at all stages of food chain, one way to improve efficiency would be to reduce each of these losses in the food supply chain in general, with the result that the same amount of food could be produced using lower doses of nutrients [13]. In this sense, in developing countries, poor storage facilities and lack of infrastructure lead to large losses after harvest and during food distribution and processing. However, in developed countries, the greatest losses occur in the final consumption phase. This is something to take into account when designing a correct strategy for food supply. Recycling nitrogen and phosphorus from waste streams, such as municipal sewage systems, manure, or industrial effluents is another potential action [14]. The technology to do that exists, but it is not equally implemented around the world. One of the biggest challenges is to implement existing technologies, with special consideration to the infrastructure that may be required, or redesigning and upgrading existing treatment systems. This is often a matter for governments due to the large costs associated with these actions. The third key action is reducing waste generated during phosphorus mining and processing. Current recovery in phosphorus mining ranges between 41 and 95% depending on the reference source [12, 15]. Focusing on increasing phosphorus recovery rate in mining, the main aspects to consider are the treatment and valorization of process water and waste streams, together with mines reclaiming. Consumption patterns have also much to do with nutrient use. In developed countries, people tend to consume much more protein that is needed according to nutritional recommendations [16]. This overconsumption indicates that there is an opportunity to reduce the intake of proteins especially of animal origin, as meat, dairy, fish, and eggs, whose production leads to high nutrient emission. Finally, the organization of economic activities also generates many opportunities to optimize the use of nutrients. An example of this is the integration of nutrient flows with different origin to encourage their more efficient use. A clear case is the traditional practice of spatial integration of livestock and arable agriculture, which offers the potential to generate synergies and improve the efficiency of nutrient recycling through the use of animal fertilizers. Another good example is the organization of nutrient production so that it is close to the final consumer, thus minimizing the losses related to deficient transport infrastructure.

3 Process options to recover residual nutrients

As stated in the section above, recycling nitrogen, phosphorus, and other nutrients from waste streams is a good option to improve the efficient use of nutrients. Manure, in general, and effluents from anaerobic digesters are important sources of nutrients. However, improper management can negatively affect environmental quality and human health. One of the main reasons for processing these streams previously to its use as fertilizer is to maximize the benefits of these products, while minimizing environmental risks. State members have paid in recent years increasing attention to investigate technologies that involve efforts for nutrient recovery and subsequent recycling from different waste sources. Figure 2 illustrates various process options, which can upcycle (that is reuse in such a way as to create a product of a higher quality or value than the original), and recover nutrients to higher quality final products.

It is usual that manure and digestate upgrading start with a physical separation generating a liquid phase (80–90%) and a solid phase (10–20%). Potassium and nitrogen tend to concentrate in the liquid phase while the solid fraction retains most of the phosphorus and the organic carbon [18]. Mechanical separation with or without addition of polymers (using drum filters, screw presses, filter belt presses, and centrifuges), thermal drying (when heat surplus is available), or evaporation to concentrate nutrients are the pre-treatment techniques more frequently used [19]. Ammonia removal from streams rich in nitrogen can be achieved by pressurized membrane filtration [20]. This technology is developed on a large scale, but it is not implemented frequently yet. Ammonia stripping-scrubbing is another technique developed at full scale for nutrient recovery from digestate and manure but not commonly used [21]. The process involves two steps. Firstly, the nitrogen in the form of ammonia is transferred from the raw stream to the air, then this ammonia is captured again in liquid form using a strong acid solution. For the economy of the process, H_2SO_4 is most often used as an acidic solution [22]. Phosphorus can be recovered from waste streams alone or together with other components, such as nitrogen. Phosphorus precipitation is the most common recovery strategy for this element and has been already implemented at full scale in several countries [23]. The addition of soluble iron or aluminum salts to a solution containing soluble phosphorus removes this component from the liquid fraction but generates salts characterized by their low solubility and low plant availability, so this is not the most interesting option when an agronomic use is the aim. On the other hand, struvite ($MgNH_4PO_4.6H_2O$) is a slow-release fertilizer produced when a magnesium source is added to the waste solution containing soluble phosphorus. Hidalgo et al. [24] compared struvite crystallization versus ammonia stripping as methods for nutrients recovery. These authors concluded that, since the crystallization process can remove and recover more than 90% P and N, at the same time, in stoichiometric ratio from

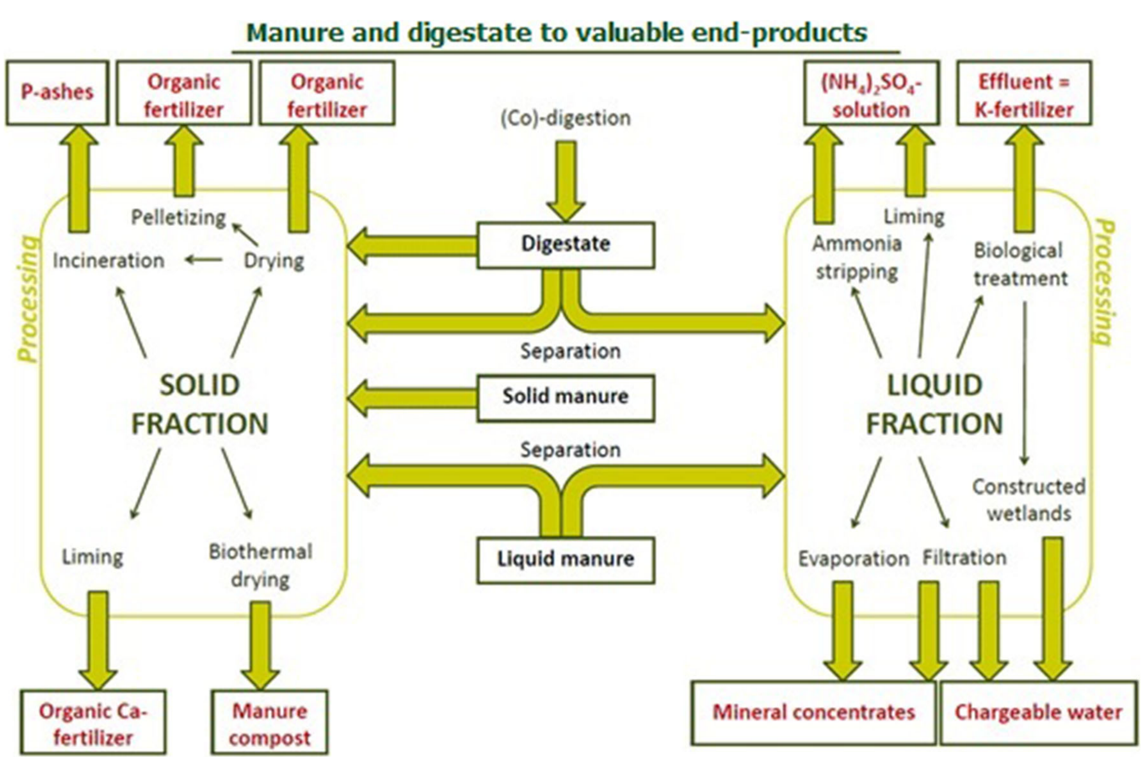

Fig. 2 Treatment processes that allow the upcycling of organic waste streams to nutrients and organic products. Source: Adapted from VCM [17]

waste streams, it could be considered the most interesting technique. Both processes are environmentally friendly and cost-effective in large-scale facilities although economic aspects slightly favor the struvite formation. Another technique for nutrient recovery is biomass production. Growing algae on nutrient-rich waste streams is a promising process since harvested algae have many potential commercial uses including fertilizers, animal feed, bioplastics, and biofuels [25]. Research is now focused on reducing the production costs to make the installations economically feasible. In the same line, macrophytes (duckweed) have also been studied as a way of recovering nutrients from waste streams [26, 27]. In reference to solid waste, techniques for phosphorus extraction from sewage sludge, manure cakes, or ashes generated in incineration, pyrolysis, or gasification processes are existing both on full scale and demonstration scale [28]. Besides the most established technologies for nutrient recovery, other promising technologies are making their way to full-scale applications and are near to the commercialization. However, there is still low awareness between the agricultural practitioners about these commercially "ready for practice" technologies drawn from high research maturity applied scientific programs. In this sense, the ongoing project NUTRIMAN [29] has collected a list of 544 matured innovative research results from the field of nitrogen and phosphorus recovery, including technologies and products [30]. A selection of the most promising ones is summarized in Table 1.

From the economic side, the methodologies traditionally used to determine the feasibility of nutrient recovery projects are usually focused only on internal costs without considering environmental externalities. This methodology usually yields a negative economic balance. However, the economic feasibility analysis taking into account the environmental benefits shows that the nutrients recovery is viable, in most of the situations, not only from sustainable development but also from an economic point of view [31, 32].

4 Novel biofertilizer products: key issues and market potential

Novel biofertilizers with direct or indirect origin in waste streams are raising much interest these days. As a result, the EC has revised the EU Fertilizer Regulation ((EC) 2003/2003), expanding its focus to secondary-raw-material-based fertilizing products, and resulting in the publication of the new EU Fertilizing Products Regulation ((EU) 2019/1009). The main policy objective of the Fertilizers Regulation Revision initiative is to incentive large-scale fertilizer production in the region from domestic organic or secondary raw materials, in line with the Circular Economy policy, by conversing by-products of the agro-food or the forestry sectors into novel fertilizers. Novel fertilizers have the potential to mitigate environmental impacts of crop production through effective nutrient recovery.

But the low farmers' knowledge, confidence, and acceptance toward novel bio-based fertilizers could compromise ambitious targets of the EU Circular Economy. Therefore, for expansion of the use of new products, "trust" and "knowledge" are needed all along the value chain: farmers should understand and know the real benefits of the bio-based fertilizers and how to practically adopt and use it in their farming practices. It is also essential to spread knowledge and information about the insufficiently exploited nutrient recovery innovations (technologies, products, practices) that are already commercially and market "ready for practice" to agricultural practitioners. This is precisely the objective of the ongoing EU project NUTRIMAN [29] that aims to identify insufficiently exploited N/P recovery innovations (technologies, products, practices) and disseminate them directly to farmers. Another initiative in this sense is the BIOREFINE project [33] that has compared novel fertilizer products with conventional fertilization scenarios. The conclusion was that the nutrients from residual sources could be successfully matched to the standards of mineral fertilizers according to the observed yields, the calculated nutrients mass balances (and the use of nutrients), as well as postharvest nitrate residues (such as indication of risks for runoff). According to these project conclusions, the future challenge with biofertilizers is mainly related to achieving stable and predictable products in terms of composition. Another key aspect of biofertilizers is to guarantee the absence of unwanted components, such as pharmaceuticals and pathogens. On the other hand, alternative composition of new products can also provide an added value. For example, considering that metals (copper, zinc, iron) are also essential plant nutrients, these compounds by themselves do not retract from the value of new biofertilizers. Another example is the presence of cadmium and arsenic in conventional fertilizers formulated from phosphate rock, but these components are less frequent in fertilizers obtained from, for example, manure. These aspects are currently investigated by the ongoing project NUTRI2CYCLE [34]. This project focuses on three pillars: agro-processing, animal husbandry, and plant processing, promoting the creation of better synergies between animal breeding and crop production. These improvements intend to facilitate the return of carbon to soil and reduce greenhouse gas emissions, which could be combined with the production of energy for self-consumption on-farm.

Nowadays, there is a special focus on three main products: struvite, biochar, and incineration ashes as potential fertilizers derived from biogenic wastes and other secondary raw materials. The EU, through different working groups (e.g., STRUBIAS), is exploring the technical and market conditions for a possible legal framework for its manufacturing and commercialization. According to recent studies [35], the agronomic efficiency of phosphate salts (e.g., struvite) is the same to

Table 1 Selected technologies/products above TRL6 for nutrient recovery [30]

P recovery	Biochar and bio-phosphate	"3R"	Animal bone char
			Biophosphate
		Pyrochar	–
	Ash	Ash leaching	LeachPhos®
		Thermal pretreatment	Ashdec
	Stuvite and other P-salts	Precipitation (BPR)	Pearl
			Asuttgart
			Airprex
			Struvia
			SCEPPHAR process
			EuPhoRe®
		Sludge leaching	Gifhorn process
			PULSE process
			AVA Cleanphos
	Other P products	Microalgae	–
		Phosphoric acid	REMONDIS TetraPHos®
			AVA Cleanphos
N&P recovery	Anaerobic digestion	HTAD	–
		AnMBR	
		CSTR	
		UASB	
	Compost	Vermicomposting	–
		In-vessel composting	
	Microalgae cultivation	HRAP system	–
		PBR system	
N recovery	Stripping and scrubbing	AMFER	–
		Poul-AR	
	Membrane concentration	GENIUS-NK	–
		VP-Hobe process	

BPR, biological phosphorus removal; *HTAD*, high-temperature anaerobic digestion; *AnMBR*, anaerobic membrane bioreactor; *CSTR*, continuous stirred tank reactor; *UASB*, upflow anaerobic sludge blanket; *HRAP*, high-rate algal pond; *PBR*, photobioreactor; *AMFER*, ammonia stripping technology from digestate for the production of ammonium sulfate; *Poul-AR*, poultry manure de-ammonification as pre-treatment for anaerobic digestion; *GENIUS-NK*, dissolved air flotation plus reverse osmosis; *VP-Hobe process*, manure processing into granular soil improver

that of mined and synthetic fertilizers. These results are consistent and can be generalized across different settings, including crop and soil types, relevant for the EU agricultural sector. In the case of thermal oxidation materials and derivates, the agronomic efficiency was overall lower than for mined and synthetic fertilizers but very dependent on the feedstock and post-processing. Thermal oxidation materials derived from crop residues and poultry litter, for example, presents better characteristics than those proceeding from sewage sludge. Observations confirm that thermal oxidation materials of residues from crops and livestock operations can deliver an appropriate alternative to mined rock phosphate and processed P-fertilizers in European agriculture. In the case of pyrolysis and gasification materials derived from slaughter by-products, crop residues, poultry litter, and pig manure, agronomic efficiency is not very different from that of fertilizers derived from raw materials. The current EU market for the technologies involving the production of struvite, biochar, and incineration ashes is mainly driven by the increased need to produce energy from alternative sources or to remove nutrients from waste streams (e.g., manure, urban wastewaters or effluents from the food industry) to reduce and prevent the leaching of nitrogen and phosphorus to water bodies. In most EU Member States, these products are not yet legally recognized as fertilizers so they cannot be commercialized, with some local exceptions. The future market of fertilizers derived from waste sources depends on the technological availability and potential constraints of the production processes, the consumer and market readiness, and the impacts throughout the new material life cycle [35]. Table 2 presents the market estimate for "recovered" fertilizers products expected to be on the market in 2030. Fertilizers derived from municipal wastewaters (60%) and manure (39%) will lead the ranking. Furthermore, it is estimated that the market for thermal oxidation materials and

Table 2 Market estimate for recovered nutrients in 2030 (P-basis). Adapted from Huygens et al. [35]

Process	Fertilizer	P recovered total (kt P/y)	P recovered bio-available (kt P/y)	Location	Market drivers
Crystallization:					
After anaerobic digestion	Precipitated phosphate salts and derivates	45	48	Livestock dense regions	Reducing externalities due to manure management, renewable energy targets
At WWTPs		29	30	Areas with strict wastewater treatment	Increased share of plants with biological treatment
From food industry		2	2	High presence of dairy and potato processing industries	Reducing costs associated with wastewater discharges
Thermal oxidation:					
Of manure	Thermal oxidation materials	39	35	Livestock dense regions	Reducing externalities due to manure management, renewable energy targets
Of sewage sludge		98	98	Regions with low acceptance for sewage sludge landspreading	Increase awareness on soil protection
Of slaughter waste		Intermediate	Intermediate	Livestock dense regions	Reducing externalities due to animal waste management, renewable energy targets
Pyrolysis:					
Of manure (solid fraction)	Pyrolysis and gasification materials	Intermediate	Intermediate	Livestock dense regions	Reducing externalities due to manure management, soil quality targets, increased market acceptance
Of slaughter by-products		Intermediate	Intermediate	Livestock dense regions	Increased market acceptance

precipitated phosphate salts, together with its derivates will grow exponentially in the coming years due to high consumer confidence in the final product and synergies with renewable energy production.

According to the preliminary market assessment, interesting market demand for recycled nutrient-based materials in different segments of the EU agricultural sector is expected. The most important part of the recovered materials will be used as fertilizer that can be used to provide nutrients, mainly phosphorus, to EU agriculture. Some materials may also fulfill other agronomic functions and include uses such as growing media, soil improvers, or culture media. Fertilizers' prices can be established according to their phosphorus content. In agreement to Huygens et al. [35], benchmark prices for these materials per ton material are estimated as follows: 158 EUR for struvite (12.6% P, 9.9% Mg, 5.7% N); 58 EUR for sewage sludge ashes (intermediate, 9%P); 69 EUR for poultry litter ashes (5.5%P); 250 EUR for calcium dihydrogen phosphate derived from sewage sludge ash (20%P); and 94 EUR for tetracalcium phosphate-like ashes (7.5%P).

5 Nutrient-related policies

Policies at all levels, no matter if they are national or international, have a key role in promoting adequate nutrient management. However, traditional practices must be overcome and new models and instruments developed to achieve the objectives of the new nutrient policy. Due to the complex chain of causes and effects in nutrient management, together with the wide diversity of markets, cultures, social agents, and organizations, it is not surprising that the same political instruments can have different results depending on the country or the region where they apply. Simple nutrient regulations may seem more effective for industry (for example, municipal water treatment and waste management) than for agriculture. The reason is clear, in the first case, there is a limited number of actors involved, which allows them to control the entire process, from production to sales, and therefore they can decide to transfer the cost of their actions related to nutrients recovery to consumers [36]. In the second case, the situation is more complex, as the number of actors involved multiplies, as well as the need for coordination when making decisions. Current policies related to nutrients, especially nitrogen and phosphorus, differ from one region of the world to the other, but what is clear is that there is a common need to improve the nutrient use efficiency in the full chain to be able to produce more food with less pollution, less energy, and less nutrient demand. According to Sutton et al. [2], each region in the word has specific characteristics when dealing with the "nutrients use" issue. In some regions with excess nutrients, recent efforts have focused on regulation to prevent pollution issues, mainly of watercourses. However, other countries have emphasized the need to provide subsidies for the purchase of fertilizers to ensure food production.

Fertilizer consumption in many parts of Latin America and sub-Saharan Africa is low, mainly due to poor market and transportation infrastructure and poor cost/benefit ratio when using fertilizers. Large investments in infrastructure and research are needed to change the situation. Both regions are characterized by a lack of farmers' access to nitrogen and phosphorus, what limits food production while increasing land degradation. There is also little investment in fertilizer production in these regions, with existing facilities focused on exporting. As a consequence, there is a need to import nutrients and take advantage of existing nutrient sources. Sub-Saharan Africa has only a weak implementation of policies to ensure adequate nutrient supply to small farms. This fact, together with the lack of an appropriate infrastructure to supply these nutrients from non-nearby sources, which also contributes to increase fertilizer prices, making them unaffordable for the farmer [37]. A similar situation is found in Latin America. The major challenge in this area is to develop policies that handle the existing polarization among the interests of small farmers versus the interests of important agribusiness [38]. Europe and North America have high exposure to the potential risk of future phosphorus shortages. In these regions, high impacts of pollution on health and the environment have also been observed due to the loss of nutrients by different means (combustion, agriculture or sewerage). Environmental policies have had a positive effect, but have substantially offset by higher consumption of animal products per capita. In the case of Europe, the conditions for the use of fertilizers have been partially harmonized by Regulation (EC) No 2003/2003 of the European Parliament and of the Council which covers, almost exclusively, inorganic material–based fertilizers both extracted from mines or chemically produced. But in order to comply with the principles of the circular economy, it would be also necessary to use recycled or organic materials for fertilization purposes. The new EC regulation goes in this direction [39, 40] and seeks harmonized conditions to make fertilizers made from such recycled or organic materials available throughout the internal market. Availability would be the first important incentive that would stimulate their use. Promoting greater use of recycled nutrients would further help the development of the circular economy and allow more efficient general use of resources. For certain recovered wastes, such as biochar, struvite, and ash-based products, a market demand for their use as fertilizer has been clearly identified. Therefore, such products should no longer be considered as waste and, consequently, it should be possible for products containing or consisting of such recovered materials to enter the market. High impacts on human health and environment or deterioration of agricultural soils are some of the negative effects found in Asia because of the excessive use of fertilizers [40]. The reason is the high nutrients releases to water, soil, and air and the imbalanced use of land (overuse and excess nitrogen in relation to other nutrients). China is a clear case. The country has exceeded optimal levels in fertilizer use in the search for increasing food production. The challenge is now to lower subsidies on fertilizer production to such a level that nutrient use is optimized by drastically reducing losses and threats of contamination, while ensuring food security [38]. In addition, taking into account the predominance of small farms in China, the increase in farm size must be integrated into the actions to achieve the objective of controlling fertilizer use [41]. In India, a "nitrogen subsidy" on fertilizer costs has directly supported local farmers. Although more action is still required in this country, the "nutrient subsidy" measure is helping to increase efficiency in nutrient use to achieve a more balanced fertilization and, at the same time, reducing pollution [42]. Table 3 summarizes the status of recycled nutrient drivers in different regions.

Table 4 shows how intense the use of nutrients is in the regions studied. Regions where there is a high availability of nutrients usually face the biggest pollution concerns, especially in relation to combustion sources (nitrogen oxides emission), agriculture (leaching), and wastewater treatment, threatening the quality of the environment in all its terms: air, water, soil, and biodiversity. Countries with less natural availability of nutrients and that work to meet the basic objectives of food security have often implemented initiatives to control fertilizer prices in order to make them more accessible to the farmers. But the results are sometimes counterproductive since the farmers tend to use an excess of nutrients in the false belief that the more nutrients the better for the harvest. This limits food production, degrading the soil and exacerbating the conversion of natural ecosystems into agricultural land. Regions with insufficient local nutrient resources intensify their efforts to improve infrastructure and control prices to ensure an adequate supply of these elements.

6 Conclusions and future trends

There are some big opportunities in all the world regions in relation to fertilizers use that can realistically be achieved. Solid waste management strategies of the developed nations are creating economic, social, and environmental opportunities for the recovery of nutrients. Markets are showing positive demand on organic fertilizers, even in less developed countries, due to the favorable policy and ideological changes and global price hikes of inorganic fertilizer. Many governments are promoting the use of the "4Rs" as a management practice for farmers. The 4Rs include correct type/source (adapt the type of fertilizer to the needs of the crop), adequate time (make nutrients available when the crop needs them), correct rate (balances the amount of fertilizer used with the real needs of

Table 3 Status of recycled nutrients sources for world regions. Source: Adapted from Sutton et al. [2]

	Agricultural sources	Sewage sources	Combustion sources
Sub-Saharan Africa	Very low per capita consumption of fertilizers, animal feed, and animal products. Recycling practices already implemented, but low quality of recycled products. P rock deposits available but lacking financing to maintain production.	Very low water consumption per capita, but non-existent support policies and lack of basic water treatment systems.	Low per capita consumption of combustion sources, but many of them are still very polluting (N oxides).
Latin America	Contrasts in social dynamics: modern agricultural businesses versus traditional smallholders, which leads to uneven use of fertilizers. Increase in bioenergy production. Increase in the consumption of animal products (grass-fed animal, meaning low feed and fertilizer consumption).	Increasing water consumption per capita, and increasing implementation of basic water treatment systems (although without an equal distribution in the region).	Air pollution problems in large cities due to biomass burning and fossil fuel-based transport.
Europe and North America	Very high per capita consumption of fertilizers, animal feed and animal products. Net import from other countries apart from intensive local production.	Very high per capita consumption of water, with advance wastewater treatment, but low recycling of sewage nutrients (N, P).	Air pollution problems in large cities due to biomass burning and fossil fuel transportation.
South and Central Asia	Unequal use of fertilizers depending on the region. Food consumption has evolved from vegetarianism to meat and from coarse grains to fine grains.	Increasing nutrient load in wastewater due to new consumption patterns, poor treatment models and uneven implementation of environmental policies.	The growing per capita consumption increases urban and industrial emissions and energy consumption. High rural emissions due to inefficient domestic combustion.
South and East Asia	Rapid increase in consumption of animal products, with the consequent increase in fertilizers and feed requirements. Low attention to nutrients recycling.	Increase in per capita consumption, decrease in the recycling trend and lack of residual effluent treatment strategies.	Increasing per capita consumption. High emissions due to inefficient combustions.

the crop), and the right place (locate nutrients where crops can use them). The efficiency in the use of nutrients is quantifiable: the more efficient their absorption is by the plant, the lesser quantity reaches as waste in the environment. Existing and future research, together with the application of 4Rs, will help in this direction and contribute to solving the nutrient challenge.

There is an urgent need to optimize nutrient cycles in all the regions to satisfy world food needs while reducing potential negative impacts to human health, ecosystems, and climate.

Table 4 Nutrients consumption per region. Source: Adapted from Sutton et al. [2]

	Annual input[1]	Crop NUE[2]	Full-chain NUE[3]	N consumption[4]
Sub-Saharan Africa	0.5 (0–2) kg P 8 (0–20) kg N	91 (29–187)	39 (4–112)	17 (1–152)
Latin America	20 (4–35) kg P 60 (0–120) kg N	26 (6–68)	22 (6–56)	39 (3–102)
Europe and North America	5 (2–10) kg P 80 (50–300) kg N	35(8–68)	22 (7–52)	60 (9–106)
South and Central Asia	3 (1–8) kg P 40 (10–200) kg N	58 (15–146)	33 (8–106)	24 (6–140)
South East Asia	45 (20–100) kg P 250 (50–1000) kg N	30 (7–79)	3 (1–42)	28 (1–408)

[1] Range and average of annual inputs per hectare of farmland

[2] Range and average of Nutrient Use Efficiency (NUE). NUE calculation is based on nitrogen content in crops as a percentage of the total nitrogen supplied with the fertilizer. Values over 70% imply “soil mining” that is agricultural land degradation

[3] Range and average of Nutrient Use Efficiency. Full-chain NUE is the total nutrients consumed as a percentage of the total inputs (fertilizer, fixation and net import)

[4] Range and average of country values. Annual per capita N global input including industrial fixation, biological N fixation combustion fixation as NOx, and net national import

There is also an increasing public pressure to reduce the environmental impacts of agricultural production. As a direct consequence, international consensus is needed to develop several urgent actions. It is essential to establish an evaluation system for the integrated analysis of the interactions that occur between nutrients in all media, whether air, land, or water, and its effects on climate and biodiversity. In this regard, the main driving forces, such as interactions with food and energy security or the costs and benefits and opportunities for the Circular Economy, should be considered. Consideration should also be given to establishing internationally agreed objectives to improve the management of nitrogen and phosphorus at regional and global levels. It is necessary to develop a consensus on indicators that allow measuring the progress in the sustainable use of nutrients and analyze the realization of improvements and the reduction of adverse environmental impacts associated with the loss of nutrients. Further research on existing options to improve the efficiency of nutrient use and develop and implement approaches to monitor the achievement of nutrient targets will help demonstrate benefits at all levels, including human health, sustainability, and food and energy supply. It is also necessary to identify the main barriers to change, as it is to promote education and public awareness in this field. Governments must quantify the multiple benefits of meeting nutrient targets for freshwater, marine, and terrestrial ecosystems, mitigating climate threats, as well as improving human health. Finally, a consensus must be developed to establish a mandate from the international community, based on the contributions of all social, political, and economic actors.

According to the preliminary market assessment, interesting market demand for recycled nutrient-based materials in different segments of the EU agricultural sector is expected. The most important part of the recovered materials will be used as fertilizer that can be used to provide nutrients, mainly phosphorus, to EU agriculture. Some materials may also fulfill other agronomic functions and include uses such as growing media or soil improvers.

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