Nutrients recycling: from waste to crop

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Abstract

In the transition from a fossil reserve-based to a bio-based economy, it has become a critical challenge to close nutrient cycles and move to more effective and sustainable resource management, both from an economical and an environmental perspective.

The production and transport of mineral fertilizers requires significant amounts of fossil energy. Hence, the dependency of agriculture on fossil reserve-based mineral fertilizers (especially N, P, and K) must be regarded as a serious threat to climate change and future human food security. On the other hand, estimates of phosphorus reserves are pessimistic. Based on population growth and future demand for nutrients, it is expected that depletion will occur within 100 to 300 years. At the same time, the agricultural demand for mineral fertilizers is continuously growing, mainly due to the increasing world population, the rising meat consumption, and the cultivation of energy crops.

Despite these unfavorable prospects, a large amount of minerals is dispersed in the environment through processing or disposal of waste streams. 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 greener economy to produce more food and energy while reducing environmental impact.

This paper will show the process options which can ‘upcycle’ and recover residual nutrients to higher grade end-products, characterized by higher nutrient use efficiency and will reveal the key issues to face with novel biofertilizer products and changing policies.

Keywords

Circular economy, nutrients cycle, biofertilizers, organic waste.

Introduction

World demand for total fertilizer nutrients (nitrogen, phosphorus and potassium) is estimated to grow at 1.9 percent per annum, reaching 202 million tons (expected) by the end of 2020 [1]. Figure 1 shows the nutrients balance situation foreseen for 2019 in different regions, calculated as the difference between fertilizers supply and demand.

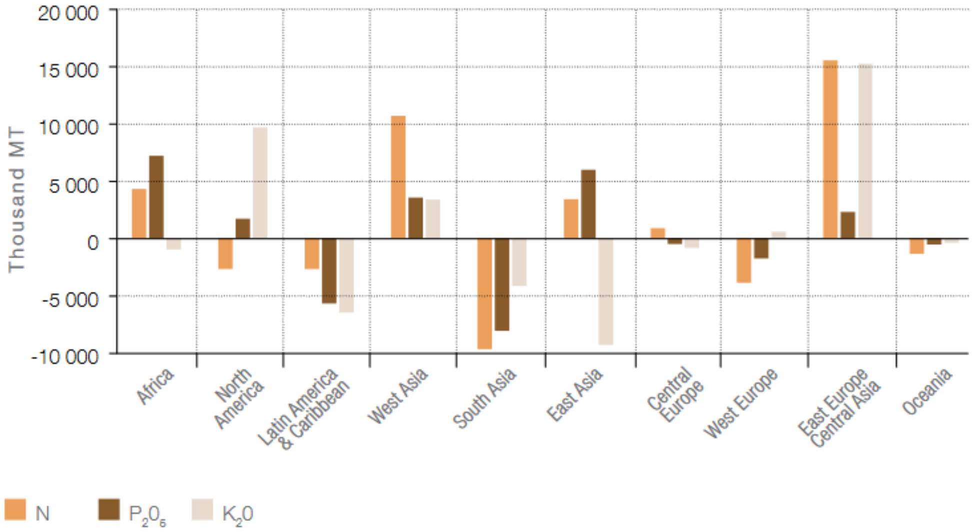

Figure 1. Regional nutrients balance foreseen in 2020. Source: [1].

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 fertilizers, while the majority produces at a subsistence level based on crop rotation, recycling of crop residues, organic wastes and animal excreta. On the other hand, in the developed world and in several rapidly developing regions of South and East Asia, there is the problem of excessive nutrient use with uncontrolled consequences.

When dealing with nutrients there are four important aspects to consider according with Sutton et al. [2]:

- In order to feed 7 billion people, the sustainability of this world depends on nutrients. Humans have more than doubled global land-based cycling of nitrogen (N) and phosphorus (P).
- The world's N and P cycles are now out of balance, causing major environmental, health and economic problems.
- Insufficient access to nutrients still limits food production and contributes to land degradation in some parts of the world, while finite P reserves represent a potential risk for future global food security, pointing to the need for their prudent use.
- Unless action is taken, increases in population and per capita consumption of energy and animal products will exacerbate nutrient losses, pollution levels and land degradation, further threatening the quality of water, air and soils, affecting climate and biodiversity.

It is clear the imminent need in developed countries for increasing the substitution of nutrients in synthetic mineral fertilizers with waste derived nutrients originating from bio-based sources. However, current manure and bio-waste treatment technologies are costly and often not aimed towards recovery of minerals. Instead they, focus on mitigating environmental pressure, which often implies removal and overall loss 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 points to the need for improved infrastructure and innovative models to improve access to nutrients for agricultural areas often distant from fertilizer production and distribution points. At the same time, efforts are needed to understand and manage the risks for long-term sustainability, considering the synergies between imported mineral fertilizer sources, manure recycling and biological nitrogen fixation [4].

Recycling energy and materials through re-connecting crop and livestock production becomes indispensable for attaining agricultural sustainability in all the senses, not only in the environmental sense. It is time to reconnect nutrient flows between crops production and livestock sectors. To do so, it is needed to invest in agro-industrial processes, which can contribute in the upcycling of mineral nutrients from organic flows towards mineral fertilizer. This approach calls for the further development of a third (after crop and animal production) agro-industrial pillar to be developed in addition to and support of the two existing main pillars of agricultural activity, namely agro-residue processing and upcycling [5].

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 production and in animal production is a good strategy, as it aims at increasing global food productions, optimizing the 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:

- Further develop and implement and the ‘4R Nutrient Management Stewardship´ developed by the fertilizer industry, i.e., the Right fertilizer, the Right amount, the Right time of application and the Right placement using low-emission application and precision placement methods. Implement 4R as function of site- specific conditions, and with full consideration of the available nutrients in soils, animal manures, crop residues and wastes [6].
- Select the right crop cultivar, planted at right spacing and right time, within the right crop rotation.
- Irrigate the crop whenever needed, using precision methods, such as drip irrigation, combined with soil water harvesting methods and soil conservation practices.
- Implement integrated weed, pest and disease management measures to minimize yield losses while protecting the environment.
- Reduce nutrient losses through site-specific mitigation measures, including erosion control measures, cover crops, tillage management, best practices for fertilizer and manure applications, and buffer strips.

These actions are targeted to advisors and farmers, but must be supported by the industry and research communities.

In reference to animal production, this was traditionally centered around homes and was conducted at small scales. However, as the demand for animal products, such as eggs, milk, and meat has grown worldwide, livestock farming has gradually become more separate, and animal production has become more intensive, particularly in developed countries. This has led to geographic concentration of animal production systems to link the feed, production, processing, distribution and marketing components more closely, particularly for the production of poultry and swine. Consequently, animal numbers on farms have grown, farms have consolidated, and manure production has increased, often exceeding the capacity of nearby cropland to efficiently recycle manure nutrients. This over-application of manure has exacerbated problems in vulnerable areas with nitrate leaching to groundwater, ammonia and nitrous oxide emissions to air and the saturation of soils with phosphorus to the point that phosphorus losses in surface flow and leaching are serious concerns [7].

The strategy of improving nutrient use efficiency in animal production can be implemented following some approaches:

- Genetic advances through breeding has improved productivity of food animals, which has led to more efficient use of ingested feeds, better partitioning nutrients into animal products as opposed to excreted waste. At the same time, advances in veterinary medicine and improvements in animal housing have resulted in healthier environments that foster better use of feed nutrients and more efficient production of animal products [8].
- Avoid over-feeding of nutrients, unnecessarily enriching manures with valuable feed N and P. Planning animal diets, using easily digestible feeds, feeding to well-established nutritional requirements, and using additives that increase feed nutrient digestibility are key actions that can improve livestock nutrient use efficiency [9].
- 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:

- Use of techniques that reduce or capture nitrogen emissions in combustion processes, such as low NOx burners or catalytic reduction.
- Use of techniques that improve fuel efficiency in the combustion process.
- Use of techniques that reduce energy requirement for fuel use.
- 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 overlaps for nitrogen and phosphorus, with the exception of operations related to phosphorus extraction (mining) and processing:

- Improving food supply efficiency and reducing food waste. It has been estimated that nearly 90% of global phosphate rock consumption is used to produce food and animal feed [12]. Since a large share of food is wasted at all stages of food chain, a reduction of each of these losses would improve efficiency of the overall food supply chain, with the result that fewer nutrients would be needed to produce the same amount of food consumed [13]. In this sense, since in developing countries poor storage facilities and lack of infrastructure lead to large losses following harvest and during distribution and processing, in developed countries there is much more food waste by consumers.

- Recycling nitrogen and phosphorus from waste streams, such as municipal sewage systems, manure or industrial effluents [14]. The technology to do that exists, but it is not equally implemented around the world. One of the greatest challenges is to implement existing technologies, especially considering the infrastructure that may be needed, or redesigning and upgrading existing treatment systems. This is often a matter for governments due to the large costs associated with these actions.
- Reducing waste from phosphorus mining and processing. Current recovery in phosphorus mining ranges between 41-95 per cent depending the reference source [12, 15]. Focusing on increasing phosphorous recovery rate in mining, the main issues are the recycling of process water, reclaiming mines and treating waste streams.

Consumption patterns have also much to do with nutrients use. In developed countries, people tend to consume much more protein that is needed according to dietary 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 nutrients emission.

Finally, the organization of human activities also provides many opportunities to optimize nutrients use. Examples of this are the integration of different nutrient flows to foster their more effect use, such as through the spatial integration of livestock and arable agriculture, thereby offering potential for improving the nutrient use efficiency of animal manures. Also, the optimization of nutrient production to be close to consumers, thereby reducing losses associated with poor transport infrastructure, is another good example.

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 impact environmental quality and human health. One of the primary reasons for processing these streams previously to its use as fertilizer is to maximize the benefits of these products, while minimizing environmental risks.

The 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 nitrogen, phosphorus and potassium to higher grade end-products, characterized by higher nutrient use efficiency in comparison.

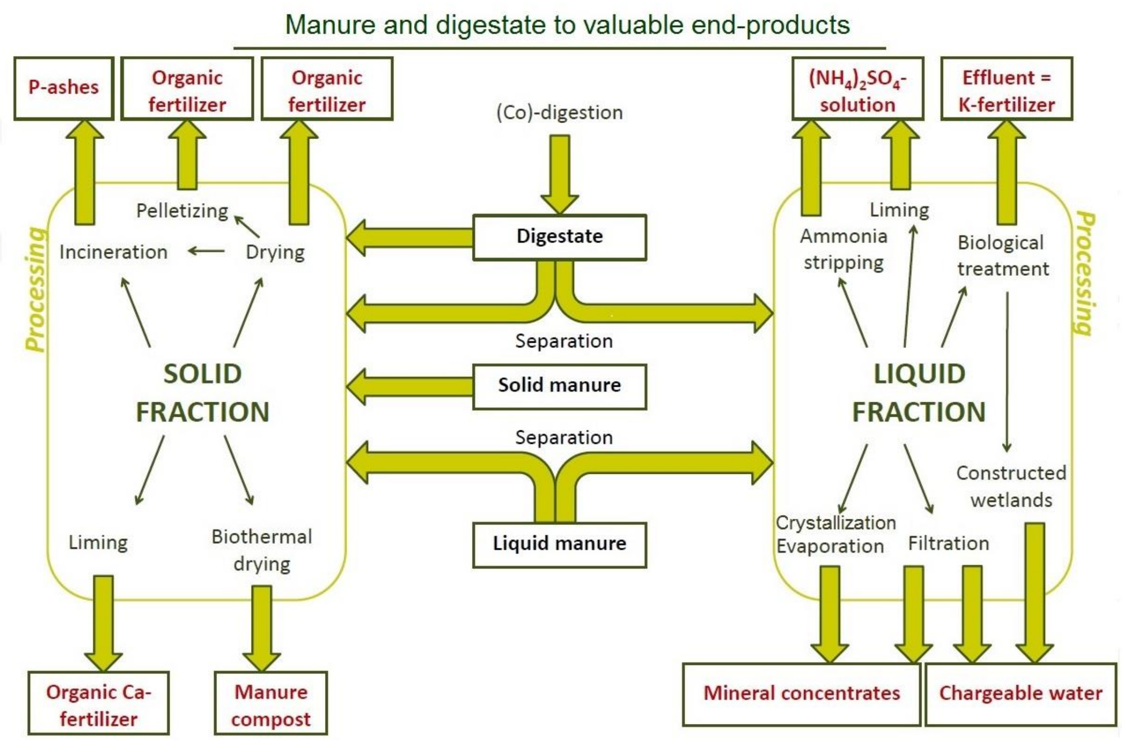

Figure 2. Treatment processes allowing upcycling organic residues to nutrients and organic products. Source: Adapted from VCM [17].

It is usual that manure and digestate upgrading start with a physical separation resulting in a liquid phase (80-90%) and a solid phase (10-20%). Nitrogen and potassium tend to end up in the liquid fraction 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 nitrogen rich liquid streams can be achieved by pressurized membrane filtration [20]. There are several types of membranes used in manure/digestate processing, which are categorized according to pore size: microfiltration-MF (pores > 0,1 μm, 0,1-3 bar), ultrafiltration-UF (pores > nm, 2-10 bar) and reverse osmosis-RO membranes (no pores, 10-100 bar). MF and UF can be used as a pre-treatment for RO. The permeate of RO, which consists mainly of water and small ions, can be discharged, if necessary after a 'polishing' step, or used as process water. This technique is developed on full-scale, but is not implemented frequently yet.

Ammonia stripping-scrubbing is another technique developed at full-scale for nutrients recovery from digestate and manure but not yet frequently used [21]. The process involves two steps. First, the nitrogen is removed by transferring volatile ammonia from the raw stream into the air, subsequently to be followed by recapturing this ammonia back to liquid form by washing the ammonia saturated air in a strong acidic solution. Due to economic reasons, most often H_2SO_4 is 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 the aim. On the other hand, struvite ($MgNH_4PO_4.6H_2O$) is a slow-release fertilizer produced when adding a magnesium source 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 simultaneously remove and recover more than 90% P and N in stoichiometric ratio from waste streams, it is considered the preferred technique. Both processes are environmentally friendly and cost-effective in large-scale facilities although economics 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 as: fertilizers, animal feed, bioplastics, biofuels, etc. [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].

From the economic side, the methodologies traditionally used to determine the feasibility of nutrients 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 [29, 30].

Novel biofertilizer products. Key issues

Novel biofertilizers with direct or indirect origin in waste streams are arousing much interest these days. The main policy objective of the Fertilizers Regulation Revision initiative in the EU 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 lower farmers' knowledge, confidence and acceptance toward novel bio-based fertilizers will undermining ambitious targets of the EU Circular Economy. Therefore for expansion of the use of new products, “trust” and "knowledge" is 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 nutrients recovery innovations (technologies, products, practices) that are already commercially and market “ready for practice” to agricultural practitioners. This is precisely the aim of the on-going EU project NUTRIMAN [31].

On the other hand, the BIOREFINE project [32] compared novel fertilizer products with conventional fertilization scenarios. The conclusion was that nutrients in organic matrices could be successfully upgraded to mineral fertilizer standards as based on observed yields, calculated nutrient mass balances (and nutrient use) as well as on post-harvest nitrate residues (as indication of unused nitrogen and hence risks for leaching). According to this project conclusions, the future challenge with biofertilizers lies predominantly in achieving stable and predictable products in regards with product composition.

Another key aspect with biofertilizers is to guarantee the absence of unwanted components, such as pharmaceuticals, pathogens, etc. On the other hand, quality aspects of new products can also provide an added value. For example, considering that metals (copper, zinc, iron, etc.) 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 retrieved from, for example, manure. These aspects are currently investigated by the on-going project NUTRI2CYCLE [33]. 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 intends 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.

Nutrient related policies

Policies, national and international, have a key role in encouraging good nutrient management. However, there is a need for exchange of information and for developing new models and instruments in many countries for achieving nutrients policy objectives.

Because of the global overview on nutrient management complex cause-effect chain, together with the huge variety in cultures, markets, civil society organizations and environments, it is no surprising that policy instruments may have different outcomes between countries. Simple nutrients regulations may appear more effective for industry (e.g., electricity generation, vehicle manufacturers, municipal water treatment) than for agriculture. This is partly because, in the first case, the number of actors is relatively low, allowing them to control both the production, marketing and sales, as well as to transfer the cost of implementing 'best techniques' to consumers [34].

Current policies related to nutrients, especially nitrogen and phosphorus, differ from one region of the world to other, but what is clear is that there is a common need to improve the full chain nutrient use efficiency and its components to be able to produce more food and energy with less pollution and less nutrients 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 too much nutrients, recent efforts have focused on regulation to avoid pollution losses. However, other countries have emphasized the need for nutrient subsidies to ensure food production.

Fertilizer consumption in many parts of Latin America and sub-Saharan Africa is low, mainly because of poor market and transport infrastructure and poor ratio cost/benefit when using fertilizers. Major investments in research and infrastructure are needed to make a difference. 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 for imports of nutrients and for development of existing nutrient sources.

Sub-Saharan Africa has only a weak implementation of policies to ensure adequate nutrients supply to small farms together with a lack of effective infrastructure to supply these nutrients from distant sources, what increases fertilizer prices making them unaffordable in many cases [35]. A similar situation is found in Latin America. The major challenge in this area is to develop policies that handle the polarization between smallholder farmers and substantial agribusiness interests in the crop and livestock sectors [36].

Europe and North America have a high exposure to potential risk of future phosphorus shortage. Also in these regions high pollution impacts on health and environment from nutrients losses from different sources (combustion, agriculture or sewage) have been observed. An increased consumption per person of animal products has substantially offset the gains from environmental policies.

In the case of the Europe, the conditions for fertilizers use have been partially harmonized through Regulation (EC) No 2003/2003 of the European Parliament and of the Council, which almost exclusively covers fertilizers from mined or chemically produced, inorganic materials. But in order to comply with the principles of circular economy, there is also a need to make use of recycled or organic materials for fertilizing purposes.

New EC regulation is looking for harmonized conditions for making fertilizers made from such recycled or organic materials available on the entire internal market in order to provide an important incentive for their further use. Promoting increased use of recycled nutrients would further aid the development of the circular economy and allow a more resource-efficient general use of nutrients. For certain recovered wastes, such as struvite, biochar, and ash-based products, a market demand for their use as fertilizing products has been clearly identified. Therefore, such products should cease to be regarded as waste, and accordingly it should be possible for products containing or consisting of such recovered waste materials to access the market. The new EC proposal for fertilizers regulation in Europe goes in this direction [37].

Very high impacts on human health and environment or deterioration of agricultural soils are some of the negative effects found in Asia reported by Rasul [38]. The reason is the high nutrients releases to air, soil and water and to 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 food security is guaranteed and nutrients use is optimized, thereby drastically reducing nutrient losses and nutrient pollution threats [36]. Also, considering the dominance of smallholder farms in China, increasing farm size should be integrated into the actions to achieve the goal of controlling fertilizer use [39].

In India a 'nitrogen subsidy' on fertilizer prices has provided support directly to farmers. While further actions are still needed, a recently introduced 'nutrient subsidy' should help to achieve a more-balanced fertilization between nutrients, increasing nutrient use efficiency and reducing pollution [40].

Table 1 summarized the status of recycled nutrient drivers in different regions.

Table 1. 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 animal products, with low fertilizer and feed inputs. High level of recycling practices, but recycled inputs limited in quantity and quality. Available P-rock deposits lack investment to support production.	Very low per capita consumption of water, but lack of policies and implementation of basic water treatment.	Low per capita consumption of combustion sources, but many them still have high emission rates.
Latin America	Social dynamics contrast: traditional small landholders versus modern agribusiness leading to uneven fertilizer use. Increasing bioenergy production and consumption of animal products, with low fertilizer and feed inputs (grass-fed beef). Little current focus on low-emission methods.	Basic sewage treatment is increasing, as well as per capita consumption of water, but basic wastewater treatment is not equally distributed in the region.	Biomass burning and transportation in urban areas (especially in megacities) are major sources of atmospheric pollution.
Europe and North America	Very high per capita consumption of animal products, requiring large fertilizer input and net feed import in many countries. Wide range of practices, including adoption of low-emission methods in a few countries.	Very high per capita consumption, with basic sewage treatment, but little recycling of sewage N, P and little tertiary N treatment in the USA.	Modern technologies have reduced NOx emissions, but very high and still increasing per capita energy consumption and transport use.
South and Central Asia	Uneven fertilizer use, food consumption shifting from coarse grains to fine grains and from vegetarianism to meat.	Increasing sewage loading due to rising per capita consumption, uneven treatment policies/strategies and their poor implementation.	Increasing per capita consumption raising urban emission from transport, energy and industry. High rural emission due to inefficient domestic fuels.
South and East Asia	Rapidly increasing per capita consumption of animal products, with increasing fertilizer and feed inputs. Low current attention to recycling and low emission opportunities.	Increasing per capita consumption, decreasing focus on recycling and lack of wastewater treatment policies.	Increasing per capita consumption, while many combustion sources have high emission rates.

Table 2 shows the intensity of nutrients use in the mentioned regions. Regions with too much nutrients availability, face major pollution problems especially from combustion sources (electricity generation, industry, transport), agriculture and wastewater treatment, threatening water, air and soil quality, climate and biodiversity. Countries working to meet core food security goals have often implemented policies to reduce fertilizer prices, but then find themselves using excess nutrients or an inappropriate balance of between nutrients. Regions with insufficient local nutrient resources struggle with costs and infrastructure to ensure adequate nutrients supply. This limits food production while risking soil nutrient mining, degrading soils, which can exacerbate the conversion of virgin ecosystems into agricultural land.

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

1. Average and range country values Annual inputs per hectare of agricultural land.
2. Average and range of Nutrient Use Efficiency (NUE) country values. National crop NUE based on N in national harvested crops as a % of the total fertilizer N input. Values in brackets are the range of national values. Values in excess of 70% imply 'soil mining' thereby degrading agricultural land for future generations.
3. Average and range of Nutrient Use Efficiency country values. National Full-chain NUE defined as nutrients consumed by humans as a % of the total inputs (fertilizer, fixation and net import).
4. Average and range of country values. Annual per capita N input including industrial fixation by the Haber-Bosch, combustion fixation as NOx, biological N fixation and net import at a national level.

Conclusions

There are some big opportunities in all the world regions in relation with 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: right source/kind (match the fertilizer type to crop needs); right time (make nutrients available when the crop needs them); right rate (match the amount of fertilizer to crop needs); and the right place (keep nutrients where crops can use them). Nutrients use efficiency is quantifiable; the more efficient the uptake of nutrients by the plant, the less escapes into the environment. Existing and future research, coupled with the application of the 4Rs, will help solve the nutrient challenge. Sharing and diffusing new technologies and practices would also help to achieve the nutrients targets.

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

The establishment of a global assessment process for nitrogen, phosphorus and other nutrient interactions between air, land, water, climate and biodiversity is a must. In this case, main driving forces should be considered, as the interactions with food and energy security, the costs and benefits and the opportunities for the Green Economy. Also the establishment of internationally agreed targets for improved nitrogen and phosphorus management at regional and planetary scales should be considered.

It is necessary to develop a consensus on the indicators to measure progress including nutrient use efficiency and comparing progress in making improvements and in reducing the adverse environmental impacts of nutrient losses. To further investigate options for improvement of nutrients use efficiency or to develop and implement approaches for monitoring achievement of the nutrient targets within different time-scales, will help to demonstrate social and economic benefits for health, environment, and the supply of food and energy.

To identify and address the major barriers to change while fostering education, multi-stakeholder discourse and public awareness is another urgent action.

Governments have to quantify the multiple benefits of meeting the nutrient targets for marine, freshwater and terrestrial ecosystems, mitigation of greenhouse gases and other climate threats, and improvement of human health. Consensus should be developed toward establishing a mandate from the international community, which draws on inputs from governments, business and industry, academia and civil society.

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References
[1] FAO: World fertilizer trends and outlook to 2020. http://www.fao.org/3/a-i6895e.pdf (2017). Accessed April 2019
[2] Sutton, M. A., Bleeker, A., Howard, C. M.: Our nutrient world: the challenge to produce more food and energy with less pollution. NERC/Centre for Ecology & Hydrology (2013)
[3] Meers, E.: How to improve the agronomic use of recycled nutrients (N and P) from livestock manure and other organic sources?. EIP-Agri Focus Group starting paper. https://ec.europa.eu/eip/agriculture/sites/agri-eip/files/eip-agri_focus_group_nutrient_recycling_starting_paper_2016_en.pdf (2016). Accessed April 2019.
[4] Vanlauwe B., Kihara J., Chivenge P., Pypers P., Coe R., Six J.: Agronomic use efficiency of N fertilizer in maize- based systems in sub-Saharan Africa within the context of integrated soil fertility management. Plant and Soil 339, 35-50 (2011)
[5] INEMAD (2013). Reconnecting livestock and crop production. https://www.wur.nl/en/show/inemad.htm. Accessed April 2019.
[6] Norton, R., Snyder, C., García, F., Murrell, T. S., Balance, P. N., Efficiency, A. Efficiency, R.: Ecological intensification and 4R nutrient stewardship: measuring impacts. Better Crops with Plant Food 101(2), 10-12 (2017)
[7] Kuhn, T., Kokemohr, L., Holm-Müller, K.: A life cycle assessment of liquid pig manure transport in line with EU regulations: A case study from Germany. Journal of Environmental Management, 217, 456-467 (2018)
[8] Sonstegard, T. S., Carlson, D., Lancto, C., Fahrenkrug, S. C.: Precision animal breeding as a sustainable, non-GMO solution for improving animal production and welfare. In Biennial Conf. Aust. Soc. Anim. Prod. 31, 316-317 (2016).
[9] Solà-Oriol, D., Gasa, J.: Feeding strategies in pig production: Sows and their piglets. Animal feed Science and Technology, 233, 34-52 (2017)
[10] Benke, A. P., Rieps, A. M., Wollmann, I., Petrova, I., Zikeli, S., Möller, K. Fertilizer value and nitrogen transfer efficiencies with clover-grass ley biomass based fertilizers. Nutrient Cycling in Agroecosystems, 107(3), 395-411. (2017).
[11] Garza-Reyes, J. A., Villarreal, B., Kumar, V., Molina Ruiz, P.: Lean and green in the transport and logistics sector–a case study of simultaneous deployment. Production Planning & Control, 27(15), 1221-1232 (2016)
[12] Chen, M., Graedel, T. E.: A half-century of global phosphorus flows, stocks, production, consumption, recycling, and environmental impacts. Global environmental change, 36, 139-152 (2016)
[13] Schott, A. B. S., Andersson, T.: Food waste minimization from a life-cycle perspective. Journal of Environmental Management, 147, 219-226 (2015)
[14] Husgafvel, R., Karjalainen, E., Linkosalmi, L., Dahl, O.: Recycling industrial residue streams into a potential new symbiosis product–The case of soil amelioration granules. Journal of cleaner production, 135, 90-96 (2016)
[15] Scholz, R. W., Wellmer, F. W.: Although there is no Physical Short-Term Scarcity of Phosphorus, its Resource Efficiency Should be Improved. Journal of Industrial Ecology, 1-10 (2018)
[16] Billen, G., Lassaletta, L., Garnier, J.: A vast range of opportunities for feeding the world in 2050: trade-off between diet, N contamination and international trade. Environmental Research Letters, 10(2), 025001 (2015)
[17] VCM: Manure to valuable end-product. http://www.vcm-mestverwerking.be (2011). Accessed January 2018.
[18] Loyon, L.: Overview of manure treatment in France. Waste Management, 61, 516-520 (2017)
[19] Gebrezgabher, S. A., Meuwissen, M. P., Kruseman, G., Lakner, D., Lansink, A. G. O.: Factors influencing adoption of manure separation technology in the Netherlands. Journal of Environmental Management, 150, 1-8 (2015)
[20] Ansari, A. J., Hai, F. I., Price, W. E., Drewes, J. E., Nghiem, L. D.: Forward osmosis as a platform for resource recovery from municipal wastewater-A critical assessment of the literature. Journal of membrane science, 529, 195-206 (2017)
[21] Eskicioglu, C., Galvagno, G., Cimon, C.: Approaches and processes for ammonia removal from side-streams of municipal effluent treatment plants. Bioresource Technology 268, 797-810 (2018)
[22] Jamaludin, Z., Rollings-Scattergood, S., Lutes, K., Vaneeckhaute, C.: Evaluation of sustainable scrubbing agents for ammonia recovery from anaerobic digestate. Bioresource Technology, 270, 596-602 (2018)
[23] Cieślik, B., Konieczka, P.: A review of phosphorus recovery methods at various steps of wastewater treatment and sewage sludge management. The concept of "no solid waste generation" and analytical methods. Journal of Cleaner Production, 142, 1728-1740 (2017)

[24] Hidalgo, D., Corona, F., Martín-Marroquín, J. M., del Álamo, J., Aguado, A.: Resource recovery from anaerobic digestate: struvite crystallisation versus ammonia stripping. Desalination and Water Treatment, 57(6), 2626-2632 (2016)
[25] Hidalgo, D., Martín-Marroquín, J. M.: Adding sustainability to the beverage industry through nature-based wastewater treatment. In Processing and Sustainability of Beverages (pp. 1-36). Woodhead Publishing (2019)
[26] Adhikari, U., Harrigan, T., Reinhold, D. M.: Use of duckweed-based constructed wetlands for nutrient recovery and pollutant reduction from dairy wastewater. Ecological Engineering, 78, 6-14 (2015)
[27] Zhao, Y., Fang, Y., Jin, Y., Huang, J. et al.: Pilot-scale comparison of four duckweed strains from different genera for potential application in nutrient recovery from wastewater and valuable biomass production. Plant Biology, 17(s1), 82-90 (2015)
[28] Thomsen, T. P., Sárossy, Z., Ahrenfeldt, J., Henriksen, U. B., Frandsen, F. J., Müller-Stöver, D. S.: Changes imposed by pyrolysis, thermal gasification and incineration on composition and phosphorus fertilizer quality of municipal sewage sludge. Journal of Environmental Management, 198, 308-318 (2017)
[29] Egle, L., Rechberger, H., Krampe, J., Zessner, M.: Phosphorus recovery from municipal wastewater: An integrated comparative technological, environmental and economic assessment of P recovery technologies. Science of the Total Environment, 571, 522-542 (2016)
[30] Yetilmezsoy, K., Ilhan, F., Kocak, E., Akbin, H. M.: Feasibility of struvite recovery process for fertilizer industry: A study of financial and economic analysis. Journal of cleaner production, 152, 88-102 (2017)
[31] NUTRIMAN: NUTRIent MANagement and Nutrient Recovery Thematic Network. www.nutriman.net (2019). Accessed April 2019.
[32] BIOREFINE Cluster: www.biorefine.eu (2017). Accessed April 2019.
[33] NUTRI2CYCLE: Transition towards a more carbon and nutrient efficient agriculture in Europe. www.nutri2cycle.eu (2018). Accessed April 2019.
[34] Oenema O., Bleeker A., Braathen N.A., Velthof, G.L.: Nitrogen in current European policies. Chapter 4 in: The European Nitrogen Assessment (Eds. Sutton M.A., Howard C.M., Erisman J.W., Billen G., Bleeker A., Grennfelt P., van Grinsven H. & Grizzetti B.), 62-81, Cambridge University Press (2011)
[35] Feder, G., Savastano, S.: Modern agricultural technology adoption in sub-Saharan Africa: A four-country analysis. In Agriculture and Rural Development in a Globalizing World (pp. 11-25). Routledge (2017)
[36] Heffer, P., Prud'homme, M.: Fertilizer Outlook 2018–2022. In 86th IFA Annual Conference, Germany (2019)
[37] EUBIA: Proposal for a regulation of the European Parliament and of the Council laying down rules on the making available on the market of CE marked fertilising products and amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009. http://data.consilium.europa.eu/doc/document/ST-15103-2018-INIT/en/pdf (2019). Accessed April 2019.
[38] Rasul, G.: Managing the food, water, and energy nexus for achieving the Sustainable Development Goals in South Asia. Environmental Development, 18, 14-25 (2016)
[39] Ju, X., Gu, B., Wu, Y., Galloway, J. N.: Reducing China's fertilizer use by increasing farm size. Global environmental change, 41, 26-32 (2016)
[40] Praveen, K. V., Aditya, K. S., Nithyashree, M. L., Sharma, A. Fertilizer subsidies in India: an insight to distribution and equity issues. Journal of Crop and Weed, 13(3), 24-31 (2017)