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Sustainable Sewage Sludge Management: From Current Practices to Emerging Nutrient Recovery Technologies

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Abstract: Nutrient recovery from secondary resources, such as wastewater, has received increasing attention in recent years. Nutrient cycle sustainability and recycling approaches are important measures under development and considerations. This paper aims to present an overview of routes and technologies for nutrient recovery from sewage sludge and measures for improving their sustainability. First, current routes for nutrient recovery from sewage sludge are briefly reviewed. Next, an overview of commercial nutrient recovery technologies, projects, and emerging techniques around the world with the key factors for a successful phosphorus recovery technology is presented. Finally, a proposal for improving the sustainability of these practices is presented. It is concluded that the gap between demand and supply can be a major driver for the shift from 'removal and treat' to 'recovery and reuse'. Moreover, there is not, and will never be, a one-size-fits-all solution. Future strategies and roadmaps need to be adapted to the local economy and geographical context more than ever.

Keywords: nutrient recovery; sewage sludge; sustainability; phosphorus recovery; nitrogen recovery

1. Introduction

Rapid population growth, climate change, urbanization, and depletion of natural resources are obliging the global society to prepare for a stressful position for some natural resources. The wastewater (WW) sector, as one of the active players, needs to identify barriers and utilize creative strategies to cope with the expected challenges in the future.

The implementation of the European Council Urban Wastewater Treatment Directive (UWWTD) 97/271/EC (21 May 1991) triggered fundamental changes in wastewater treatment [1]. The ban on sludge dumping in the sea and limits for phosphorus and nitrogen discharge demanded more effective treatment methods and new infrastructures to address the increased volume of sludge. During recent years, on the one hand, population growth has led to a higher demand putting more pressure on resource supply and the environment [2], and on the other hand, legal, environmental and economic drivers have encouraged recovery and transformation of resources from wastewater into valuable products.

Wastewater contains nutrients vital for human food production. Modern agriculture is dependent on the massive use of mineral fertilizers (NPK fertilizers). The Haber–Bosch process and mining of phosphate rocks have been the most commonly used approaches to produce nitrogen-based and phosphorus-based fertilizers, respectively. Food production accounts for 90% of the mineral phosphorus consumption in Europe, split between fertilizers (79%) and livestock farming (11%). The ineffective use of P-fertilizers in food production has been stated in several studies. For instance, it has been stated that in Europe it takes 4 kg of reactive phosphorus to produce 1 kg as food with 40% surplus ending up in the soil and 50% loss from the system (17% to waterbodies), or in China it takes 13 kg of reactive phosphorus to produce 1 kg of food [3,4]. This reflects a not sustainable strategy with a subsidized and inefficient use of reactive phosphorus. In addition, phosphate rocks, which are the main source of P, are non-renewable and in the risk of depletion due to the expected population growth. The timeline of depletion of phosphate rocks has been disputed, but this should not distract from the instant effects of poor resource management. Phosphorus management strategies should be considered for several reasons, regardless of the exact time of global phosphate rocks depletion. Phosphorus has no substitute in agriculture, and in several locations (especially the tropics) the access to the P still limits the agricultural productivity. Moreover, there has been price instability for inorganic phosphate fertilizers with potential for future turbulence (i.e., food price spike) [5]. The world's population will increase 1.3 times by 2050 [6] with three times more phosphorus demand to produce enough food for the growing population [7]. Quality phosphate rocks are available in only a few countries, and the European Commission added phosphate rocks to the list of 20 Critical Raw Materials back in 2014 [8] for which supply security is at risk, and economic importance is high. Phosphorus recovery from wastewater is one effective strategy to compensate for the increasing demand and to slow down the depletion rate of phosphate rocks [9].

Among waste sources, such as animal feeding, crop farming, industrial pre-treatment facilities, septic systems, stormwater and wastewater treatment plants (WWTPs), nutrient recovery (NR) from wastewater and sewage sludge has been the most practiced approach and has received significant attention over the last decades due to practical considerations and available infrastructure at WWTPs. However, sewage sludge produced in a wastewater treatment process carries not only nutrients but also hazardous organic and inorganic pollutants, and this must be considered before any application.

This study describes the current practices and status of handling nutrients in wastewater and an overview of nutrient recovery practices, projects, and commercial technologies in various parts of the world. Further, a proposal for improving the sustainability of these practices is presented.

2. Methodology

This work aims to present an overview of nutrient recovery routes from sewage sludge and current practices and emerging technologies for nutrient recovery. Challenges and opportunities in the implementation phase of the nutrient recovery approach was considered as a ground to propose the requirements for a sustainable nutrient management strategy (recovery and recycling). The presented study mainly covers centralized infrastructures and technologies that are already implemented or at the brink to the market. Therefore, decentralized infrastructures or technologies at research stage were not addressed in this study. The data collected and analyzed from the available literature (reference list) and the market intelligence is based on direct contacts with technology suppliers and utilities operating the different technologies.

3. Nutrient Recovery Routes from Sewage Sludge

Currently, some nutrients in WW sludge are being recycled back to agricultural soils via direct land application, generally after treatments, such as composting, liming, and/or anaerobic digestion. This approach, however, has drawbacks, such as lack of full confidence about the consistency and nutrient content and availability as well as human health risks arising from the presence of pathogens, organic contaminants, and heavy metals in land-applied sludge.

The most practiced routes for capturing nutrients from wastewater are concentrating them in biomass (biological treatment or algae), or physicochemical separation. Reject liquid from sludge treatment (sidestream) in a typical municipal WWTP has 7 to 12 times higher N and P concertation as compared to the mainstream and therefore, is the first target for NR due to smaller volume and better recovery rates. However, different N and P concentrations have been stated in other studies, too [10,11].

Principally, in the current phosphorus removal methods, reactive phosphorus is removed from wastewater by converting soluble phosphorus (mainly orthophosphates, PO_4-P) to a solid state that becomes a part of the total suspended solids (TSS) and is removed as sludge. The sludge may be further treated to solubilize the captured phosphorus and make it available for recovery purposes. Strategies that are only based on P-removal cannot be entirely sustainable and may cause operational and treatment difficulties in wastewater treatment plants.

Theoretically, phosphorus recovery is possible from the liquid phase, sludge, and sludge ashes. Ninety percent to ninety-five percent of the incoming phosphorus is incorporated into the sludge, and phosphorus recovery from the liquid phase at the current stage of development will not exceed 20% to 40% while P-recovery technologies from the sewage sludge and sludge ash have a higher potential for P-recovery [12]. It seems essential that more innovative methods with higher efficiency for recycling of phosphorus should be developed and applied.

Figure 1 illustrates prominent and already applied concepts for P-recovery and recycling from sewage sludge. Discussion on these alternatives and their pros and cons is not the aim of this paper. Struvite precipitation from sludge liquor or sidestream has been proven viable for various WWTP operations. Mostly, it is an enhanced biological phosphorus removal (EBPR) process combined with anaerobic digestion followed by struvite precipitation on sludge liquor [13].

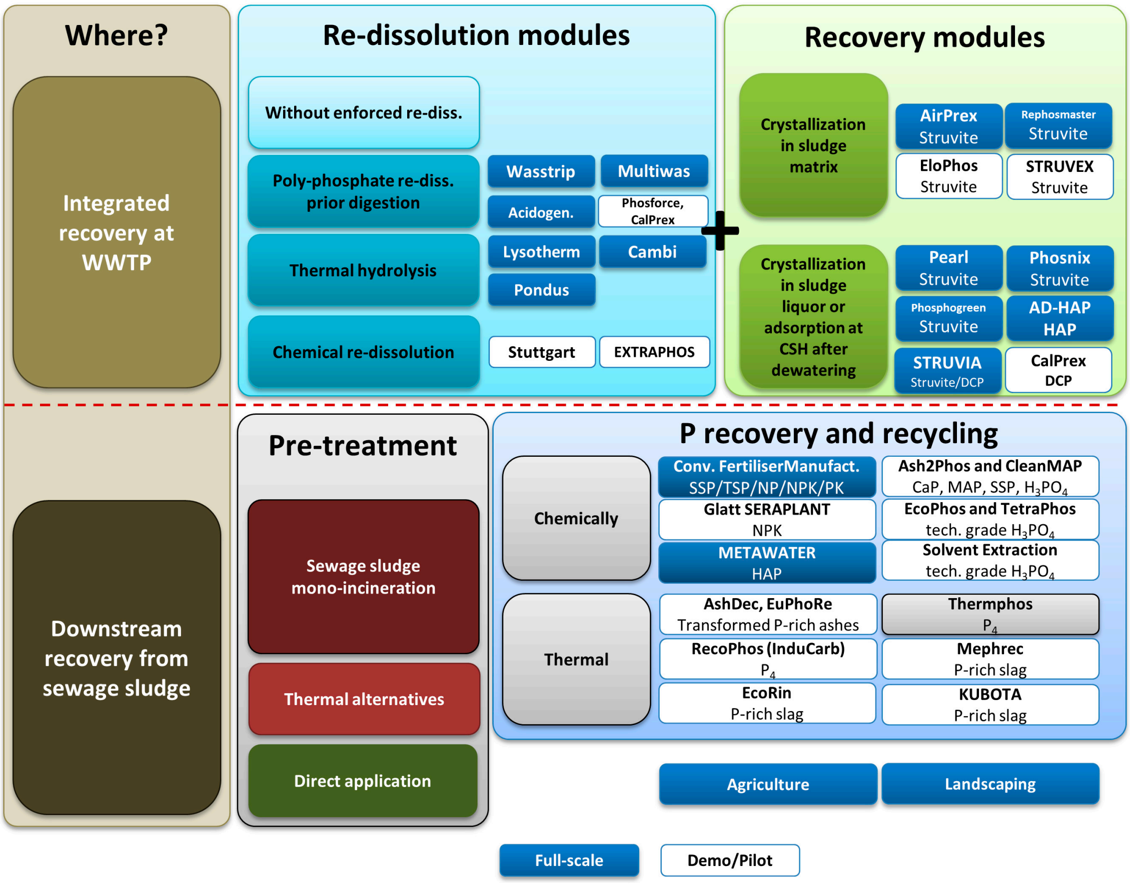

Figure 1. Prominent and already applied concepts for P-recovery and recycling from sewage sludge (Adapted from [14]).

The main goal of nitrogen recovery (i.e., reactive nitrogen recovery) is to short circuit the nitrogen cycle and to convert nitrogen in WWTP sidestreams to artificial fertilizer (precursors). In this way, the production of nitrogen fertilizer may be reduced with positive environmental impacts. Preferred recovered compounds are ammonium sulfate or ammonium nitrate. These products are suitable when the agricultural soil has a surplus of phosphorus. The amount of nitrogen in the reject water depends on the sludge type as well as the extent and configuration of the wastewater treatment. About 30% of the nitrogen in the sidestream, accounting for 4% of the nitrogen in wastewater, can be recovered [15,16]. Although this is far less than the agriculture needs for artificial fertilizer, N-recovery from wastewater might be part of a bigger sustainable solution. Ammonia synthesis from N_2 and H_2 via the Haber–Bosch process is energy intensive. Moreover, while nitrogen is abundant in the atmosphere, natural gas as the main source of hydrogen is non-renewable. Therefore, the conventional approach, i.e., removing ammonia from wastewater as nitrogen gas and then synthesizing ammonia from nitrogen and hydrogen to produce N-fertilizer, should be revised to enhance the overall energy efficiency, increase N-cycle sustainability, and satisfy greenhouse gas regulations and goals.

In general, short-circuiting of the nitrogen cycle is technically possible, but not very favorable from the energy point of view. From the cost perspective, the large amount of required chemicals makes the present and expected future technologies noncompetitive. Nevertheless, in special cases with the availability of residual chemicals or waste heat, N-recovery can be cost-effective and sustainable. There is a need for new techniques with reduced use of electricity, heat, and/or chemicals to have a more competitive and feasible N-recovery process for sidestream of WWTPs in the future.

4. State-of-the-Art and Current Practices around the Globe

4.1. Current Practices

For years, sewage sludge treatment has been considered a secondary issue compared to main wastewater treatment. However, importance of sludge management, is on the rise due to the fast increase of sludge generation owing to sewage network extensions, new installations, and upgrading of facilities [17]. Wastewater or treated wastewater effluent has been used in some countries as an alternative for irrigation to moderate the water use and to recover nutrients and water at the same time. However, the associated risks should be properly assessed owing to the extensive risk of wastewater reuse in agriculture. This requires the consideration of local regulations and to ensure that the pollutants will not be transferred to soil. Further, possible alterations of the soil texture properties, biomass, and microbiota should be considered [18].

Our review shows that global sewage sludge management can be classified into three different levels: developed, developing, and undeveloped. The common strategies are (1) no recycling (landfill, storage, dumping), (2) substance reuse (drying, land use), (3) substance conversion (compositing, anaerobic digestion, incineration, and wet oxidation), and (4) nutrient/energy recovery (incineration, anaerobic digestion, gasification) [19]. Europe, North America, and East Asia are the main sludge producers in the world [17]. Land application as the major route for the use of sewage sludge in western members of the EU has now been banned in several countries (Germany, Netherlands). In the USA about 55% of the produced sludge is applied to soil for agronomic and land restoration, and 45% is in municipal solid waste (MSW) landfills and incineration plants. However, the broad perspective on the management of biosolids has changed a little in recent years in the USA. In South America, little priority has been given to sewage sludge management due to a shortage of legal bases and basic facilities [17]. There is a lack of attention to sewage sludge management in Africa, with the exception of South Africa, due to lack of regulations and economic support where landfilling or direct discharge to the environment are the most common practices. The approaches for sewage sludge management are different in Southeast Asia. This varies from a poor situation in some countries to well-designed treatment systems in others due to the variety in population and development level of countries in this region. The current approaches in Japan and South Korea as two neighboring developed countries present a major contrast. Incineration of sewage sludge (70%) and landfill application are main disposal routes in Japan, while in South Korea sewage sludge was dumped into the sea until 2012 and currently there is a shift towards landfill application [20]. The favored option in China is land application due to disposal cost and environmental benefits [17].

The management of sewage sludge varies in different countries due to dissimilar social, economic, and technical contexts. Wastewater networks and wastewater treatment plants are essential infrastructures for the realization of the nutrient recovery from sewage sludge. Still, low-cost solutions have been preferred by utilities except for limited cases owing to the introduction of legal frameworks from authorities. The level of urbanization, livestock density index, and available land area are important factors in the selection of a favored strategy for sewage sludge management. Land application of sewage sludge can reduce the sludge disposal cost significantly. This approach is mainly practiced in an area with low population density and abundant available land, while high population density and limited land encourages alternative routes, such as nutrient recovery and product export (Netherlands, Singapore). For instance, a country, such as India, with a huge population requires a mature sanitation system as a prerequisite for the implementation of sludge management. Eastern Europe countries are in the stage of implementation, while a proper state of centralized sanitation in Western Europe has paved the way for the implementation of nutrient recovery from sewage sludge.

4.2. Emerging Technologies

Despite having a major potential for contributing to better nutrition management, the nutrient recovery sector is still facing a variety of issues on the business level, including legislative challenges, public awareness, and marketability of recovered material. Nevertheless, NR technologies have undergone accelerated development in the past decade, mainly due to operational benefits, increased environmental awareness, supply security, and stricter discharge limits on these nutrients.

N-recovery has received less attention than P-recovery due to lower operational need and economic motivation. At the current stage, the extraction of only N is cost-effective when ammonia has an immediate use on site [21]. However, in the years to come, N-recovery will gear up, especially for the case of manure, where the nutrient loads are much higher compared to sewage sludge.

Figure 2 presents an overview of the main products and commercial technologies for phosphorus recovery [14]. The most applied approach is struvite precipitation from the sludge sidestream or industrial WW (mainly food processing) with high P concentration, followed by calcium phosphate precipitation, and phosphoric acid production [21]. P-recovery, especially in treatment plants with enhanced biological phosphorus removal (EBPR) and anaerobic digestion may help improve plant economy via improved sludge treatment and dewaterability and additional income due to product sales. An improved plant operation (reliability) by lowering the operational challenges (blockage frequency of valves and pipes) is the additional driver. Other technologies are still either in research (laboratory) or development (pilot) phase, improving maturity, lowering costs, and gathering data for full-scale design.

Figure 3 presents some of the key factors that define the success of a P-recovery technology or a class of technologies, which should be considered for comparison and evaluation of different processes. A well-defined product and market potential (ready-to-use product or a compatible raw material for industry) should be considered when evaluating a technology (known product). The proper power for successful rollout (rollout potential) and general applicability in existing systems will increase the chance of success (applicability). A high P-recovery rate and high purity (recovery rate) and low/moderate investment cost (cost of implementation) along with low/moderate operation cost and low amounts of waste generated (operating costs) are essential elements for success of a technology. In addition, societal and political acceptance (societal acceptance) and side benefits, such as reduced operational costs (side benefits), are also necessary for a sustainable business in the P-recovery sector [22].

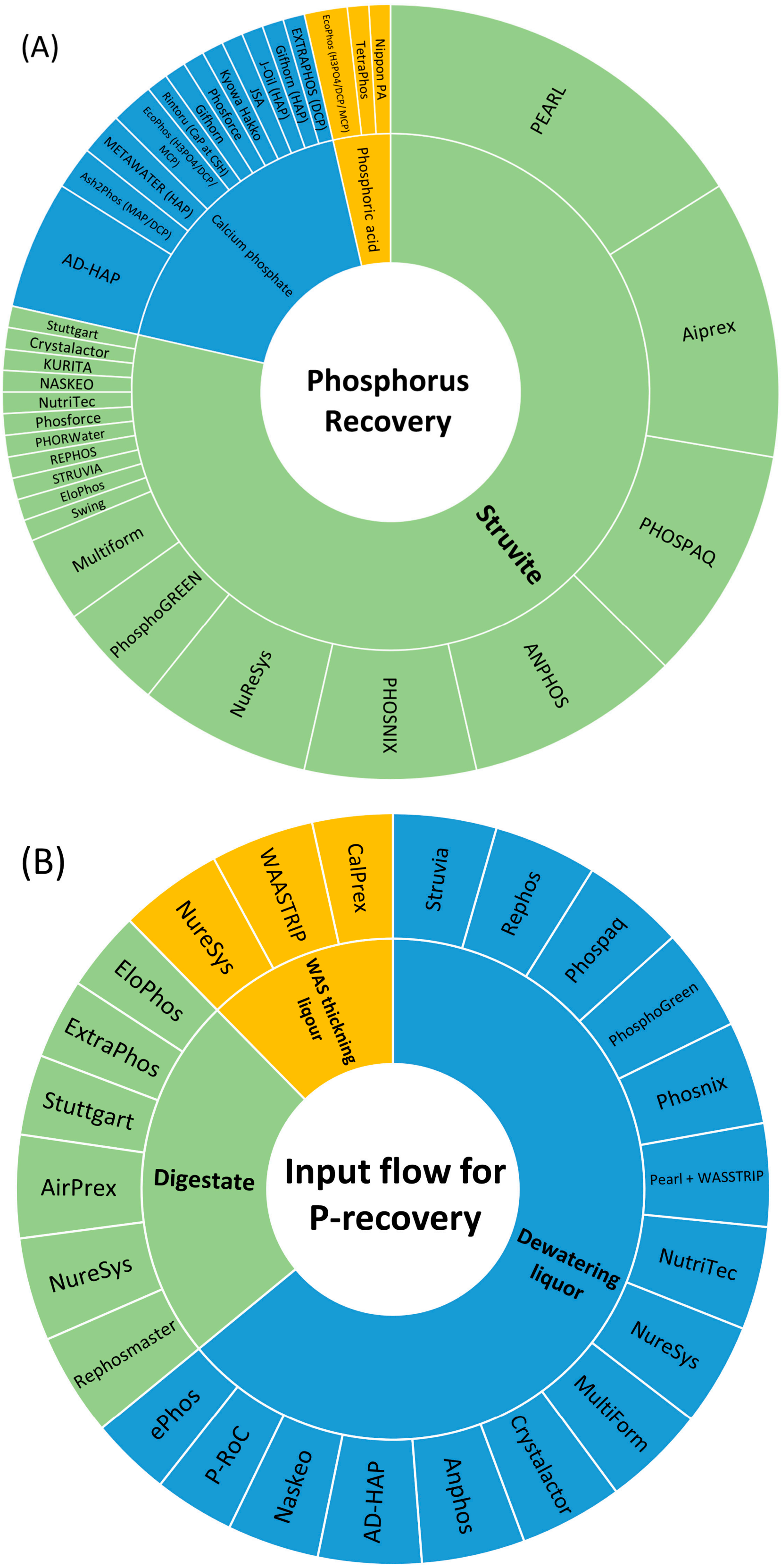

Figure 2. (**A**) Overview of the main products and the commercial technologies for phosphorus recovery, where area dedicated to each technology corresponds to the number of facilities in operation. (**B**) The input flow for P-recovery in different P-recovery technologies.

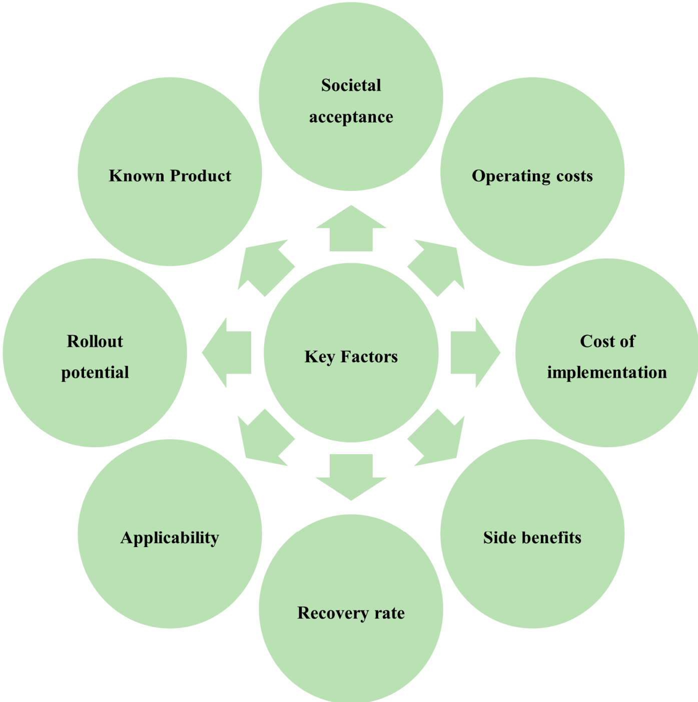

Figure 3. The key factors for the success of a P-recovery technology.

4.3. Current Global Status

Despite lack of strong financial drivers, the number of full-scale operational nutrient recovery units in WWTPs has been continuously increasing in the past decade with the majority of them in developed countries and installed on sludge liquor stream. Table 1 presents a high-level summary of NR practices and projects around the world. The EU is the region with the highest number of installed full-scale units followed by North America and Japan [23]. The EU is also the leading area based on number of full-scale installations predominantly producing struvite, although the volume of recovered struvite is currently higher in North America. Figure 4 presents the worldwide map of operational plants for P-recovery, among all of which more than 80 plants recover struvite, and more than 60 plants are municipal wastewater treatment plants. Normally, it is expected that phosphorus scarcity stimulates the recovery and recycling of phosphorus, although the available installations are in the countries or regions with a nutrient surplus, often linked to excessive livestock farming, limited land area, and high population density [14].

The EU commission has an extensive program for sustainable nutrient recovery (from bio-waste) and reuse, under which several platforms and projects are undertaking (or already have been undertaken) research, development, and commercialization of NR technologies. Japan is an early mover that since the 1980s has realized the importance, potential, and advantages of P-recovery. In Japan, strong nationwide collaborative programs between industry, academia, and government are in place, and business models and market development strategies for integrated P-recovery and recycling from WWTPs, steel production, agriculture, and chemical industries have been established producing both struvite and calcium phosphate (HAP: hydroxyapatite) [24,25]. Learning and adapting Japan's experiences in the NR sector could be a useful strategy for other regions and countries. Records on NR units in other parts of the world are scarce. Wastewater collection and treatment is still undeveloped or under development in several regions in the world which contribute to a significant percentage of the world's population, especially in rural areas. Therefore, the prevalence of NR would only be conceivable in a long-term perspective.

Table 1. Overview of some of nutrient recovery practices and projects in various parts of the world adopted mainly from [21,23].

Geographical Area	Plants	Technology/Product	Remarks
North America	More than 15 full-scale units mainly producing struvite	Pearl, Multiform, Airprex see [10]	Lack of economic drivers and regulations for nutrient recovery [10]
Europe	Germany (10), Netherlands (10), Belgium (6), France (2), Spain (2), Italy (1), UK (2), Denmark (4)	Variety of technologies including Airprex, Anphos, Elophos see [10]	Mainly producing struvite from both municipal and industrial wastewater
China and India	China (Tianjin, Nanjing), India nor record found	Airprex, Crystalactor	China is planning new facilities with biological phosphorus removal and anaerobic digestion for energy recovery
Africa	No plants, feasibility studies in South Africa on P-recovery from sludge and source separated urine	NA	High costs, immature market and lack of acceptability
Japan	16 full-scale plants producing struvite and calcium phosphate	Gifu, PHOSNIX	Strong nationwide collaboration on market development, integrated production from steel, agriculture and chemical industries

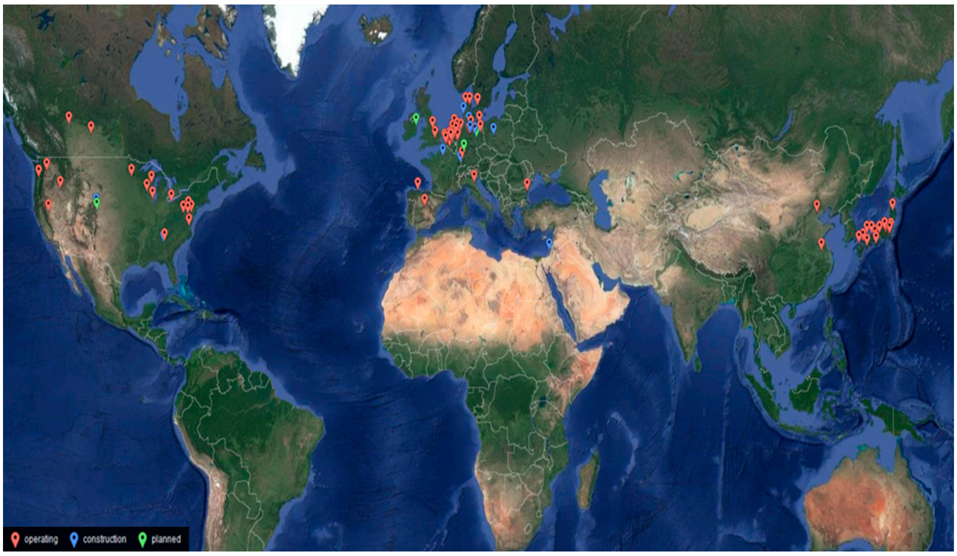

Figure 4. The worldwide map of operational plants for P-recovery [26].

It can be concluded that the low market price for fertilizers from phosphate rocks challenge the economic viability of nutrient recovery technologies, especially when the candidate technology does not provide additional operational benefits or a directly marketable product. The integration potential of a technology or a recovered material into existing infrastructure increases the chance to be in the successful class technologies. The direct involvement of potential users is as an important factor to reduce the complication of the emerging technologies and increase the chance for market deployment. Moreover, the higher recovery rates and additional operational benefits are important factors that should be considered in the development of the new generations of nutrient recovery technologies [22].

5. Implementation—Challenges and Opportunities

5.1. Environmental Regulations

Environmental legislation can be a key driver to accelerate the recycling and recovery of resources where the additional associated costs are against it. However, the current legal frameworks are mainly tailored to the existing structures. Thus, proper adjustment is necessary for adaption to the future challenges. Germany in 2017 and Switzerland in 2016 announced legal requirements for P-recovery. The EU fertilizer regulation (EC 2003/2003) is an example of such a regulation that can support the quicker transition towards nutrient recovery from wastewater. The way of monitoring and enforcing the discharge limits should be relevant and flexible. The phosphorus recovery from wastewater requires a proper and realistic discharge criterion since, where absolutely no flexibility is given to the plant operator, the final choice may be chemical P-removal rather than biological P-removal which reduces the potential for recovery.

5.2. Technical and Operational Aspects

The current trend shows that P-recovery has been mainly implemented in the case of operational needs or due to the reduction of operational costs. The current incentives for on-site nutrient recovery were recognized as prevention of uncontrolled scaling along the sludge train, improvement of sludge dewaterability, reduced polymer consumption, reduced sludge volume for disposal, partly better energy recovery, and better compliance with regulations. Excessive livestock farming and lack of land area for disposal of the sewage sludge may affect the selection of P-recovery technique. This is because the nutrients in the sludge exceeding the capacity or demand for domestic agriculture may make the concentration or volume reduction of the nutrients through incineration or thermal mineralization relevant options. Therefore, in the case of sludge incineration, technical needs for plant owners are not the driver; it is the compliance with regulation and/or cost reduction for disposal. To manage the investment risks, the recovery technologies and recovered materials should have the potential to be integrated into existing infrastructure and market with minimum change to the current operational regime. Moreover, the downstream market potential and security of supply of the raw material are crucial factors that determine the vulnerability of recovery technology.

5.3. Sustainability Outlook

A sustainable phosphorus management strategy requires recovery and recycling. There are several technologies for recovery and recycling available, while under current conditions, only some of them are economically viable. The process stability and momentary benefits (mainly cost reduction) are the main drivers for implementation of current recovery techniques rather than the sole recovery of phosphorus. However, expected regulatory policies can accelerate the transition towards more comprehensive recovery and recycling in the future. A few countries are frontrunners in nutrient recovery from wastewater. However, there is a visible demand for streamlining global knowledge to cover nutrient recovery from wastewater as well as other relevant nutrient containing wastes. There is a need to have a better link between stakeholders, policymakers, and researchers to bridge the gap between knowledge and practice. Figure 5 is an attempt to illustrate a high-level strategy for sustainable development of NR from sewage sludge. The overall strategy for the NR sector forms a nutshell in which four main elements; technology, policies and legislations, market and economy; interact with their corresponding stakeholders, i.e., investors, politicians, legislators, consumers, technology vendors as well as research and development and academia. This strategy has incorporated the key challenges that the NR sector is facing today and has proposed some proper high-level actions addressing those challenges. These actions have been predominantly formulated by taking into consideration the requirements of "sustainability" as the governing approach (3Ps: people, planet, and prosperity), such as creating/sustaining jobs, development of rural areas while promoting fair mechanisms for legislation, and rewarding mechanisms for involvement of stakeholders that are hesitant to contribute. This is in line with similar studies which proposed a 5R strategy (Re-align P inputs, Reduce P losses, Recycle P in bio-resources, Recover P in wastes, and Redefine P in food systems) to achieve a more sustainable P use [27]. In brief, it is necessary to secure economic routes to utilize secondary P in agricultural stores and consider wastewater as a potentially valuable source of P rather than a waste product and to develop sustainability indicators which are needed for long-term P sustainability.

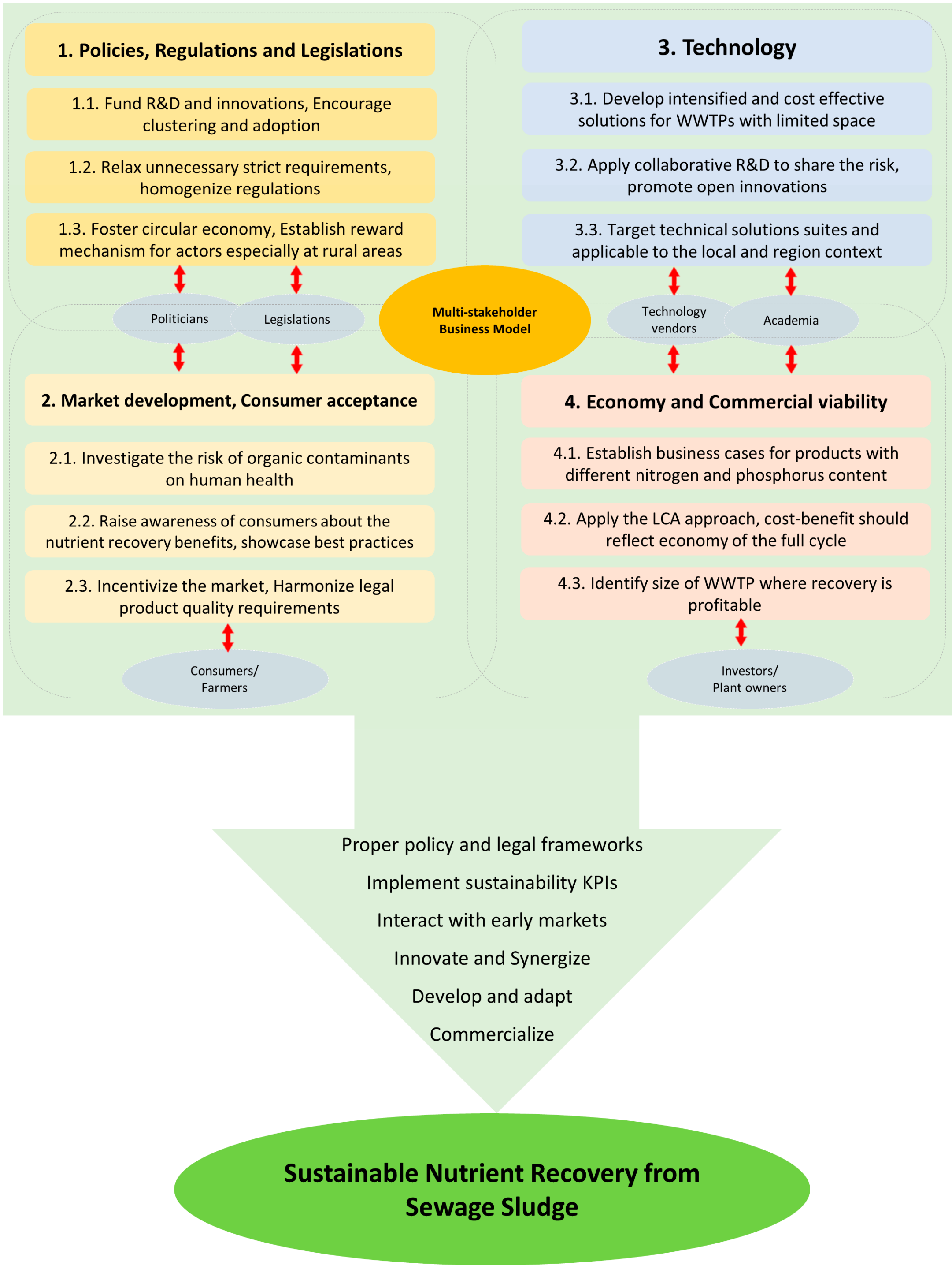

Figure 5. The proposed high-level strategy for sustainable development of nutrient recovery from sewage sludge.

6. Conclusion

Where wastewater is considered a renewable resource, nutrient recovery from sewage sludge requires a sustainable approach by utilization of appropriate technical options. Applicable strategies and roadmaps need to be adapted to the local or regional economy and geographical context. This is important to protect and improve the water quality, to enhance the operation and performance of waste treatment units, and to improve food security. Marketing of produced fertilizer from waste resources could be beyond the WWTP operators' job, and relevant stakeholders should be involved.

There is no one-size-fits-all solution, while there is a definite need to facilitate collective actions by developing business models that involve all stakeholders.

Sustainable development of the nutrient recovery sector will have to be defined based on three pillars of sustainability (3 P's) namely People (societal), Planet (ecological), Prosperity (economy); covering key aspects of this vision with the aim of the aspirational goal to reach a "zero net impact" associated with nutrient discharge from WW sludge. Achieving this goal over the coming years requires a dedication to overcome not only the technical barriers and financial constraints but also regulatory disincentives and societal aspects limiting NR from WWTPs. There will be more than one paradigm shift necessary to achieve the goal of a sustainable circular economy. Sustainability measures should be developed for WWTPs via measurable sustainability indicators (greenhouse gas and carbon footprints), monitoring and certification of the plants based on those key performance indicators (KPIs).

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