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Removal, Recovery and Reuse of Resource in Waste Streams: Challenges, Management and Solutions

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Abstract

The concept of resource recovery has received immense attention in the last decade from researchers globally due to the stringent discharge limit of nutrients, the provision of an alternative for the highly expensive inorganic fertilizers and as well as reduction of environmental pollution. Resource recovery has given wastewater a new look as a resource from which values can be derived. However, it is faced with an array of issues, ranging from technological feasibilities of recoveries, social-cultural acceptance, economic and business feasibilities, legislative-political challenges, marketability of the recovered products and environmental-ecological challenges. In this study these challenges are highlighted, considered and evaluated for possible solutions. The technological aspects are considered in the form of the source of recovery, methods and techniques as wsell as the applicability of the recovered products. A decisive aspect is enlightenment via education to change people's perspectives and attitudes towards the application of recovered products. Other challenges are also stated and reviewed and solutions are proffer to militate these challenges if properly considered. Finally, as there is not one single, encompassing solution for these challenges as some are localized and geographical, solutions therefore, must be tailor-made to fit and adapt to the challenge at hand.

Keywords: Resource and Nutrients, Removal and Recovery Technologies, Removal and Recovery Challenges, Resource Reuse Challenges, Management and Solution Practices, Sustainability

Introduction

A resource is a substance that can be transformed into a useful product or used to produce something useful or can be used. The concept of resource recovery as a solution to the menace of nutrient pollution in waste streams has over the years gained the interest of researchers globally [1-4]. Resource recovery has given wastewater a new look as a resource instead of a waste from which values can be derived. Nutrient recovery as a process can provide an alternative for the highly expensive inorganic fertilizers as well as the recovery of Phosphorus (P), Potassium (K) and Nitrogen (N) for other industrial applications apart from the reduction of environmental pollution [5-7]. For instance, P is a vital, non-renewable finite resource whose exploitable source has been predicted to become depleted within the next 45-100 years and as such P recovery from waste streams is important for sustainable development. This is because phosphate rock prices have skyrocketed, and getting a good grade phosphate rock in the market becoming difficult [8-9]. One of the critical raw materials in the EU market is Phosphate [10].

Environmental Impacts of Nutrients in Liquid Streams

The presence of nutrients (N/P) in waste streams has indeed posed a great threat to the ecosystem. Early research on increasing nutrients in aqua ecosystems assumed that waterways and lakes were resistant to excessive mineral inputs. [11-12]. Based on the idea that other physical, chemical, and biotic aspects of the system regulated the effects of nutrient enrichment on the growth of aquatic plants and algae, this statement was developed. Because of the expected limitation of potential responses to nutrient enrichment caused by ambient light levels and shorter hydraulic residence times, streams and rivers were assumed to be already nutrient-filled [13]. However, a number of studies have provided scientific evidence that excess nutrients do affect flowing waters [14–16]. Frequent releases of nitrogen and phosphorus into aquatic habitats cause eutrophication, a global issue that degrades aquatic system quality. Reduced water transparency and low dissolved oxygen (DO) levels are two problems linked to eutrophication. Nutrients' capacity to cause eutrophication in an aquatic system depends on how bioavailable they are. The only form of phosphorus that autotrophs can directly absorb is soluble orthophosphate (PO_4-P) [18]. However, phosphorus is lost from soils into the aquatic system in both particulate and dissolved forms. In aquatic systems, eutrophication is supported by the mineralization reaction that transforms particulate forms of P into orthophosphate. When it comes to nitrogen, the forms that are biologically available are ammonia (NH_3–N) and nitrate (NO_3–N), and any organic nitrogen (organic–N) is converted to NH_3–N. NH_3–N has the ability to influence DO concentrations in aquatic systems that receive fertilizer inputs from wastewater.

Lehman et al.'s study [19] found that in the lower San Joaquin River in California, NH3–N accounted for 60% of the total oxygen demand. According to Passell et al. [20], nitrogen pollution in an alkaline aquatic system can worsen NH3-N toxicity and jeopardize the survival of a variety of fish species. The usage of lakes, ponds, and reservoirs for recreational, industrial, agricultural irrigation, fishing, and drinking water may be hampered by this process. According to estimates, eutrophication-related declines in water quality have already decreased biodiversity in wetlands, lakes, and rivers by almost one-third globally, with the majority of cases occurring in China, Japan, Europe, Southern Africa, and South Asia [21]. The industries that rely on clean water are negatively impacted by nutrient pollution.[17, 22]

In addition to the problem of eutrophication, methemoglobinemia, sometimes known as blue baby syndrome, has been connected to nitrogen pollution. Methemoglobin, which is created when nitrate and haemoglobin combine, prevents oxygen from reaching tissues, leading to asphyxia (a shortage of oxygen) and cyanosis of bodily tissues. Blue infant syndrome cases linked to nitrate-N poisoning in drinking water have been documented. In 1998, a case of methemoglobinemia was reported by a Colombian hospital due to the use of well water tainted with 22.9 mg/L of nitrate-N while preparing a baby's meal [23]. In Eastern Europe, infant exposure to nitrate-contaminated water is a prevalent public health concern. Between 1990 and 1994, Ayebo et al. [24] discovered that the Transylvania area of Romania had methemoglobinemia incidence rates ranging from 24 to 363 instances per 100,000 live births. 90% of the 239 baby methemoglobinemia cases in Poland that were studied. According to the proposed mechanism, nitrate is converted to nitrite, which is then followed by the group's transition into nitrosamines. In an ecologic analysis of cancer incidence in the United Kingdom, Barrett et al. [29] found that locations with elevated nitrate concentrations had higher rates of malignancies of the brain and central nervous system, but they were unable to confirm a link between nitrate exposure and gastric cancer. According to Ward et al. [30], prolonged exposure to drinking water tainted with nitrates may raise the incidence of non-Hodgkin lymphoma. Therefore, it is essential to remove nutrients from wastewater to prevent eutrophication of water bodies and lessen the health risks that come with it.

Sources of Nutrients

i. Agricultural and Domestic Sources

It has been observed that several human endeavors, including domestic and agricultural work, raise the nutrient load in waste streams. Nutrient-rich wastewater is produced in large quantities in the agricultural sector by aquaculture, pig farms, chicken houses, wool scours, abattoirs, and maize fiber processing operations. The high P and NH^{4+} content of agricultural wastes is advantageous for nutrient recovery. According to reports, about 70% of animal feed that is consumed is expelled as urine and feces, which include organic matter, micronutrients, N, P, and K [31]. According to studies, the average total P content of dairy, pig, and poultry manures is 18 g kg^{-1}, 9.3, and 39 g kg^{-1}, respectively. [32]. Fertilizer is applied by farmers to increase crop yields and growth, however the crop does not absorb all of the nutrients in the fertilizer. Runoffs carry the leftover nutrients from the soil into the aquatic system.

ii. Industrial and Municipal Sources

Both in urban and rural areas, industrialization is rapidly expanding on a global scale. Numerous industrial processes result in effluents that are highly concentrated in nutrients. Industries that produce large amounts of waste products with high COD, BOD, and nutrients include those that make wine, fermentation products, paper, baker's yeast, and other items. For instance, 11,057x103kL of winery effluent with 116 kT P are produced annually in the United States [33]. These companies' effluent has a total nitrogen content ranging from 100 to 4535 mg/L [34–35].

Nutrient Recovery from Aqua System

Environmental, economic, and population expansion among other factors have made it necessary and more important than ever to recover nutrients from waste resources, particularly wastewater and sewage sludge, and turn them into useful goods. Many large-scale nutrient recovery projects from sludge and/or liquor streams are being established worldwide, with a significant portion of these operations located in industrialized nations like the EU, North America, and Japan [36]. The area of nutrient recovery is multifaceted, involving expert contributions from the natural and biological sciences, engineering (including environmental, mechanical, and civil), and computer science for automated control systems. The purpose of this section is to address some of the numerous obstacles that prevent nutrient recovery from aqua systems and, in the process, provide workable solutions. In this paper, nitrogen and phosphorus are the nutrients of interest. The recovery of nutrients from aqua streams is being hampered by a number of obstacles, including those that are technological, economic, social-cultural, legal, ecological, and environmental.

Technological Challenges of Nutrient Recovery

- **Sources of Nutrient Recovery**

The form and nature of the waste streams have a significant impact on the technological processes involved in nutrient recovery [17]. Animal dung and wastes from slaughterhouses and chicken farms, crop and plant leftovers, municipal solid wastes, and industrial sources are among the sources of economically valuable nutrients. According to Table 1, the sources of nutrient recovery for the past ten years have been liquid phase (sludge liquor), sewage sludge, and sewage sludge ashes.

Liquid phase: Very low nutrient concentrations (< 10 mg/L), a large volume of wastewater that needs to be treated, and low recovery efficiency (10–40%) limit the amount of nutrients that can be recovered from sludge liquor [37–38].

Sewage sludge: The following factors limit the amount of nutrients that can be recovered from sewage sludge: (i) a high concentration of contaminants, such as pathogens, toxic organic compounds, and heavy metals, which makes the products that can be recovered unsuitable for use in industry or agriculture. Sewage sludge ash: Nutrient recovery from sewage sludge ash is quite costly and has imitations that are comparable to sewage sludge.

Table 1: Summary of Sources of Nutrients for Recovery

Recovery Source	Nutrients Concentration	Recovery Potential	Constraints
Liquid Phase	Less than 100mg/l	10-40%	Low recovery Huge volume of sludge Presence of heavy metals and toxic substances
Sewage sludge	About 10g/kg	80%	High pollutant load. High capital cost
Sewage sludge ash	64g/kg	90%	High energy consumption

- **Methods of nutrient recovery**

The first step in recovering nutrients from waste streams is their removal. The technique employed to remove the nutrient affects how well the recovery proceeds. Numerous techniques, including chemical, biological, and physical ones, have been developed to extract nutrients from wastewater. Some are at large-scale treatment facilities, whereas others are only process-engineering system experiments [39]. The methods include chemical precipitation and crystallization [40], adsorption [41–43], anaerobic digestion, ion exchange, membrane filtration [44–45], electrodialysis and electrocoagulation [45], and biological processes like wetland [46–49] and enhanced biological phosphate removal [46–49] that depend on biomass growth (bacteria, algae, and plants).

(a) Nutrient Removal

Chemical precipitation: The most popular method of chemical nutrient removal, particularly for P, is chemical precipitation, which typically entails injecting metal salts into pre-treated wastewater, traditional activated sludge (CAS) reactors, or the secondary clarifier's output [50]. Nutrients bound to colloids can be chemically precipitated via flocculation and coagulation, which precipitates the nutrients as particles that settle in clarifiers and separate them. Metal salts of calcium, magnesium, aluminium, or iron are used as precipitating reagents in this method. Precipitation of PO4-P by ferric chloride and aluminium sulphate (alum) metal salts is a commonly used and recognized wastewater treatment technique. Due to the massive volume of sludge created during the process, particularly when lime is used as the precipitant, the amount of phosphorus that can be removed by chemical precipitation is limited [51]. Additional difficulties with chemical precipitation include handling hazardous chemicals and dosage, recovering P from sludge is challenging, etc.

Biological nutrient removal: In municipal wastewater treatment facilities, biological nutrient removal processes—particularly EBPR—have established themselves as reliable technologies. The enhanced phosphorus removal process is hindered by several factors, including microbial competition between glycogen-accumulating organisms (GAOs) and polyphosphate-accumulating organisms (PAOs), a large reactor requirement, high investment costs, and a significant reduction in sludge production (10%) and chemical usage. The process can remove up to 95% of P from wastewater.

Removal by Physical methods: Physical techniques of removal, like the membrane approach, are constrained by the high energy requirements, high cost of purchasing and replacing membranes, and huge sludge formation. (a) Recovering Nutrients. According to Von der Hoek et al., [8], there are now four (4) processes involved in the principles of nutrient recovery for both phosphorus and nitrogen found in aqua system technologies [34, 54-56]:

- Direct recovery from wastewater;
- Treatment of sewage sludge;
- Increasing recovery through nutrient concentration in side stream process water;
- Incorporating nutrients into biomass.

For the purpose of recovering nutrients from waste streams, a number of technologies have been put forth and put into practice on a large and bench scale. For example, well-established recovery procedures include precipitation/crystallization for phosphorus recovery from struvite and N stripping followed by absorption for ammonium sulphate recovery [57]. The three main P/N recovery technologies are thermal treatment, wet chemical (thermochemical) treatment, and crystallization.

Crystallization Methods: Full-scale crystallization has been employed in multiple plants to recover P/N from sewage liquor (rich side stream effluents) and has shown to be economically beneficial. Using crystallization technique, wastewater is dosed with metal salts (Ca, Mg, Al, or Fe) until supersaturation takes place, at which point the salt is transformed from an aqueous solution into solid crystal materials.

Wet chemical Methods: Using chemicals (acids and bases) to dissolve, leach, release, or remove bound nutrients from sewage sludge or sludge ash is known as wet chemical treatment. The enormous volume of chemicals used and the multiple processing processes needed make this recovery approach expensive and difficult.

Thermochemical Methods: This technique's primary goals are to extract heavy metals from the ash from sewage sludge and to make the nutrients in the ash more bioavailable to plants. The procedures that are involved are hydrolysis, pyrolysis, gasification, incineration, and wet oxidation. This method has an extremely high P recovery potential (>90%). Unfortunately, because of the enormous energy consumption, the procedure is only relevant to ashes that were burned in a single setting and cannot be used on a large scale. Table 2 presents a summary of the various technology approaches. The most advantageous of these techniques is thermochemical treatment since it has a high recovery efficiency and can handle a variety of input sources. The problem with the thermochemical approach is that it requires a significant initial investment and has not yet been widely used. Because they require expensive chemicals, crystallization and wet chemical treatment are less advantageous for recovering materials from municipal wastewater.

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Table 2: Summary of Methods of Recovery

Technology	Recovery Potential	Constraints
Crystallization	Fair	Metals remain in the sludge Recovery rate is 40% maximum Sludge handling and disposal problem
Wet chemical	Very good	Process is complex Huge financial investment is required Requires large amount of chemicals Requires many process steps Not economical on small scale
Thermochemical	Excellent	Process is complex Requires incineration of the sludge Requires huge amount of energy Operated only on large scale, not economical on small scale Limited to only mono-incinerated sludge

- **Recovered Products**

The type of product recovered is significantly influenced and determined by its application in agriculture. While phosphorus can be recovered as struvite ($MgNH_4PO_4.6H_2O$) and calcium phosphate (hydroxyapatite), ammonium sulphate or ammonium nitrate is the preferred nitrogen-recovered product. Struvite is often recovered as a stable white orthorhombic material from EBPR plants in a wastewater treatment facility. Due to the inherent nutrients (N and P) in the wastewater, struvite generation is a favourable reaction in many wastewater treatment plants [51]. Different firms (like Ostara) have successfully marketed struvite crystallization; the EU leads in this regard in terms of the number of full-scale installations; but, at the moment, North America has a bigger amount of recovered struvite. The following intrinsic advantages of struvite crystallization are promoted: (i) avoids operational issues resulting from struvite deposition that is not favourable; (ii) makes the sludge more dewaterable; and (iii) lowers the nutrient load on the treatment plant. Uncontrolled struvite development clogs the inner surfaces of the treatment plant and pipes, resulting in an ineffective and costly process. In addition to ensuring environmental sustainability, a planned and regulated recovery of the nutrients (P/N) as struvite in the wastewater treatment plant reduces undesired struvite deposits in anaerobic digestion and post-digestion operations.

. ***Calcium phosphates:*** Calcium phosphates, such as hydroxyapatite, are used as direct substitutes for other nutrients in industrial applications and can also be mixed with other nutrients to create a slow-release fertilizer for use in agriculture. Sewage Sludge/ Sewage Sludge Ash: Biosolids is another name for sewage sludge ash. Biosolids' inherent fertilizer contents are crucial for direct land application as soil conditioners in sustainable farming methods. Higher soil organic matter levels are created and maintained by sewage sludge ash, which improves the physical condition of the soil, restores its health, and activates its biological activity. Biosolids improve soil's ability to retain water on its surface and decrease runoff. It has a great potential for nutrients and is a viable substitute source.

The main issue with using biosolids as fertilizer in agriculture is that they include a high concentration of heavy metals, organic compounds, pharmaceuticals, and infections, which can be harmful to the environment and human health. Despite being used in the commercial sector for nitrogen recovery, struvite precipitation faces two significant obstacles: (i) Low wastewater P-concentration: Low P-concentration (> 100 mg/L) considerably impacts (decreases) the recovery process's efficiency (>40%) as well as its kinetics. [58–60] (ii) Toxic contaminants (organic and heavy metal) are present. Because of the compromised purity, this significantly prohibits the recovered products from being used in agricultural applications [61–62]. Table 3 presents a summary of the products that were retrieved.

Table 3: Summary of Recovered Products

Recovered Products	**Constraints**
Struvite	Low organic matter content Spontaneous production fouls and clogs pipes
Calcium phosphates	Not suitable for municipal wastewater Production affected by the presence of carbonate A high pH and excessive Ca^{2+} concentration is needed. Low organic matter content
Sewage sludge/ Sewage sludge ash	High heavy metal content in sewage sludge Increased cost for treatment (incineration) to produce ash

(C) Nutrient Reuse

- **Application of Recovered products**

The recovered products must be safe, ecologically acceptable, and have demonstrated agronomic efficacy in addition to being economically feasible. Any of the following characteristics make a product unfit for use as fertilizer: (i) low P/N content; (ii) high heavy metal content; or (iii) poor chemical quality. Anaerobic digestion biosolids, for example, are considered an appealing recovered product with a high nutritional content (about 4% P and 2% N). Due to the presence of viruses, hazardous organics, and heavy metals, using biosolids in agriculture has raised worries about the environment and human health.

Case Studies of Some Current Technological Nutrients Recovery Processes and Products

Table 4 lists some of the nutrient recovery methods that are now in use; some are in the development stage, some are already fully operational on a large industrial scale, and some are only useful in lab settings.

Table 4: Some Current Technological P/N Recovery Processes and Recovered Products

Process Name	Source	Recovery Potential	Technological Method	Recovered Product	Technological Purpose	Stage	Reference
PHOSTRIP	Sludge liquor	>9-%	Anaerobic P-dissolution from Bio-P sludge	CaP	Calcium phosphate precipitation from sludge liquor	Semi Industrial Scale	[63]
OSTARA PEARL	Sludge liquor	80-90%	Crystallization with addition of $MgCl_2$. Crystallization of pellets (seeds) in fluidized bed and its withdrawal	Struvite MAP Fertilizer	P , N recovery as fertilizer	Industrial scale	[64]
CRYSTALACTOR	Sludge liquor	>90%	Crystallization of pellets (seeds) in fluidized bed and its withdrawal	CaP/ MAP	P , N recovery as fertilizer	Industrial scale	[65]
UNITIKA PHOSNIX	Sludge liquor	80-90%	Crystallization with addition of $Mg(OH)_2$	Struvite	P ,N recovery from waste stream	Industrial scale	[66]
PROPHOS	Sludge liquor		Adsorption with (Calcium silicate hydrate) CSH in batch mode	CaP in CSH	Calcium phosphate precipitation from sludge liquor	Semi Industrial Scale	
PRISA	Sludge liquor	>90%	Precipitation from sludge liquid and dissolution from thickener; 25-40°C, pH 8-9, <1 h.	MAP fertilizer 12% P, 5% N, K. Struvite, Fe / Ca phosphate	P , N recovery as fertilizer	Semi Industrial Scale	[67]
PHOSIEDI	Sludge liquor	>90%	Ion exchange. pH>8, <1hr	CaP fertilizer	P recovery from wastewater	Laboratory scale	[68]
FIXPHOS	Sludge	21-31%	Crystallization.	CaP on	P recovery from	Laboratory	[69]

	liquor		Dosage of CSH inflow on sludge liquor. CaP crystallization on CSH, Separation after digestion	CSH	wastewater	scale	
BIOCON	Digested Sludge	>85	Wet chemical extraction with H_2SO_4 , removal of heavy metal via ion exchange)	Phosphoric acid	P , N recovery as fertilizer	Semi-industrial scale	[69]
BIOLEACHING	Digested sludge	>40%	Special bacteria dissolve and accumulate from ash in Bio-P-bacteria. Precipitation and anaerobic dissolution.	MAP	P , N recovery as fertilizer	Semi-industrial scale	[71]
PASCH	Digested Sludge		HCl dissolution, solvent extraction, precipitation as phosphate	MAP	P , N recovery as fertilizer	Semi-industrial scale	[72]
SEPHOS	Digested Sludge	>85	Wet chemical (leaching with acid and precipitation with base (NaOH)	CaP / AlP	P , N recovery as fertilizer	Laboratory scale	[57]
SEABORNE	Digested Sludge	>80%	Acidic dissolution, separation and precipitation. 25-200°C, pH1-3, <1hr	MAP	P recovery from wastewater	Semi-industrial scale	[73]
AQUA RECI	Digested Sludge	>90%	P-dissolution at 374°C, 220 bar	FeP/ CaP	P recovery from wastewater	Industrial scale	[74]
PHOXAN	Digested Sludge	>80%	Wet oxidation, membrane separation	Phosphoric acid	P recovery from wastewater	Semi industrial scale	[75]
CAMBI	Digested Sludge	>90%	Thermochemical P dissolution and release.	FeP, AlP, CaP	P recovery from wastewater	Semi industrial scale	[76]
KREPRO	Digested Sludge	>90%	Acidification, hydrolysis dissolution and release.	FeP. No fertilizer	P recovery from wastewater	Semi industrial scale	[77]
MEMPHREC	Sewage sludge ash	>90	Thermal (Incineration) treatment in a blast furnace	CaP fertilizer	P , N recovery as fertilizer	Semi-industrial scale	[78]
THEMPHOS	Sewage sludge ash		Thermal treatment of sewage sludge ash	P (Elemental)	P recovery	Full scale	[79]
ASH DEC	Sewage sludge ash	>90%	Thermochemical treatment of ash with use of $CaCl_2$ or $MgCl_2$ in a kiln	Sewage sludge ash	P , N recovery as fertilizer	Semi industrial scale	[81]

Source: Adopted from Sartorius et al., [57]; Shaddel et al., [81].

Managing Technological Challenges of Nutrient Recovery

Despite the significant progress made in previous decays, three major problems remain: enhancing the efficacy of nutrient recovery operations, decreasing operating costs, and producing marketable products with value additions. The industry's only goal is to create cost-effective technology that can generate recovered items of marketable grade. High recovery rates, high product purity, low to moderate implementation costs, low to moderate operating costs, minimal waste generation, and high product acceptance by society are the criteria used to evaluate a successful nutrient recovery technology [81]. Large operating expenses, high energy consumption, low nutrient concentration in wastewater, and poor marketable recovered product are the main constraints on technological processes.

- **Managing the Challenges of Source Materials**

The source material is essentially where nutrition recovery begins. Similarly, plant effluent is where nutrient recovery in a sewage plant begins. When nitrogen recovery is implemented at the plant effluent, it typically results in low nutrient concentrations (P/N) since larger sewage plants remove nutrients from the effluent stream. Therefore, it is recommended that nutrients not be removed from the wastewater stream to maximize the potential for recovery from the effluent. P-recovery from the sewage plant's side streams, or sewage sludge and its liquor, is given precedence over P-recovery from the plant effluent.

Since nutrient recovery from sewage ash has the best recovery efficiency among the three steps of recovery in the treatment plant, it is preferred and advised (see Table 1). Furthermore, because of the ash's incineration and thermometallurgical processes, the recovered product is purer than others in terms of its organic pollutant and heavy metal concentrations. As a result, fertilizer can be made directly from the processed ash. This procedure produces no waste, hence there are no disposal costs. For these reasons, it is thought that P-recovery from sludge ash is preferable to P extraction from sludge.

Acien et al., [82] reported the successful use of the microalgae-bacteria consortium to fully extract N and P from wastewater streams and convert the nutrients into usable biomass (feed and biofertilizer) using solar power. The relevance of microalgae-based techniques for recovering nutrients from wastewater is recommended due to their advantages. On a small scale, this method is feasible by Min et al. [83] and Godos et al. [84]. According to their findings, in a mild climate, manure can be converted into valuable compounds using microalgae as a raw material. Furthermore, minimal energy requirements also have an extra benefit. In agricultural activities, the nutrients recovered are frequently employed in part place of artificial N/P-based fertilizers.

Unquestionably, a project called "PURALGA" in Spain showed how to produce biofertilizers from raw manure using mostly microalgae-based methods [85]. The usefulness of Sulphate Reducing Bacteria (SRB) for phosphate release from Fe-P sludge has also been documented by Suschka et al. [86]. These strategies help deal with the difficulties posed by large financial outlays.

According to Wolgast [87], annually, an average person excretes urine which corresponds to the amount of fertilizer needed to produce 250 kg of cereal. The application of human excrement as fertilizers in agriculture is changing into a preferred trend in some countries [88-96]. Jonsson et al., [97] opined that human urine is a valuable source of fertilizer in the growth of leafy vegetables. The comprehensive literature review on the appraisal of human excreta for plant growth by Heinonen-Tanski and van Wijk-Sijbesma [98] recommended human urine as a “free” fertilizer, for use in agriculture because of its high nitrogen content. Some of the inhibitions towards the use of urine recycling include storage and handling problems, issues of hygiene, increase in salinity and electrical conductivity of the treated soils. Solutions proffer for these valid reasons include:

- No direct contact between urine and crop (plant)
- Proper storage, characterization and treatment of urine before use
- Hand washing after working with urine is strongly recommended.
- Soil should be tested and characterized before application to ascertain the amount needed

With a recovery rate of 100% P and 83% N promised, the option of using human urine as a source of nutrients should not be neglected nor discarded.

- **Managing the Challenges of Methods of Recovery**

The current trend indicates that many of the novel and less developed technologies, like adsorption, ion-exchange, gas-permeable membranes, and magnetic techniques, lack nutrient recovery approaches. Integrating these technologies with well-established release methods, like anaerobic digestion, and extraction/recovery procedures, like chemical crystallization, should be the goal of future studies. As previously mentioned, bioaccumulation of N/P utilizing sulphur-reducing bacteria and microalgae is also seen to be a potential method. Technological approaches for minimizing sludge and recovering other products from sludge have been studied and documented [99–102]. Sludge quantities were decreased and sludge quality was improved using the Kemicond technique [103]. Currently, no single technique is able to fully and efficiently recover every nutrient from a waste stream.

- **Managing the Challenges of Recovered Products**

Industrialists and farmers, as end users, have interests that should be taken into consideration while handling the difficulties associated with recovered products. It is becoming more and more crucial that the recovered product be generated in a way that satisfies the needs of the agricultural and industrial sectors while having a high nutrient content, low moisture content, and extremely minimal contamination from heavy metals and pathogens. For diversification, selectivity aimed at recovering new items may be taken into consideration. For example, phosphoric acid was segregated by electrodialysis rather than phosphate, and ammonia solution was recovered using membrane distillation in an alkaline environment instead of struvite, according to Jorgensen and Weatherley [104]. Higher-quality nutrient products were produced as a result of these selective nutrient recovery systems.

A number of EU nations have outlawed the use of sludge in agriculture because of its low quality contents. High-purity sewage ash can be produced by (i) burning organic contaminants and pathogens away, and (ii) switching between anaerobic and aerobic conditions. In these circumstances, the majority of organic materials undergo oxidation and conversion to CO2 [107]. This is followed by chemical digestion (wet oxidation) to eliminate the heavy metals, such as the Cambi Process. It is also beneficial to dewater the biosolids or digest them into granulated or pelletized fertilizer products. In order to better control the N and P content of the biosolids to meet requirements, final thermal treatments (pyrolysis) at high temperatures aid in reducing the load of nutrients in the biosolids. The products (struvite, CaP, or aqueous ammonia and derived ammonium salts), are stable with minimal organic content and reduced bulkiness. Thus the products will be less costly to store and transport. Solar drying can help to reduce energy demand.

To manage the challenges faced by technology of nutrient recovery:

i. Research should be targeted at improving the efficiency of recovery of systems such as

KREPRO, BioCon, Seaborne and Aqua-Reci especially in the area of sludge minimization

ii. Research should be targeted at the use of other alternative material sources of recovery with high potentials and contents of nutrients. This will reduce operating costs. For instance, microalgae, human excreta etc as already discussed.

iii. Development of highly tradable, selective recovered materials for specific needs packaged for ease of movement and transportation.

Legislative Challenges of Nutrient Recovery and its Management

Regulations can be a stimulating factor either for or against nutrient recovery from the waste stream. Some countries have attitudes towards nutrient recovery that are impaired or are against the development of technologies or the use of recovered nutrients. Stricter conditions towards the discharge of nutrients directly into waterways by industries will definitely promote their recoveries. Nutrient recovery technology development in a nation would reduce its dependency on imported nutrients, increase its agricultural and political stability and play a significant role in employment. There are national and international directives, regulations, limits and permits on fertilizing limits, sewage sludge use in agriculture and environmental permits. Depending on the needs of each country, these restrictions are applied differently, which results in a variety of solutions and markets for organic fertilizer. The recovery procedures and the utilization of the recovered nutrients are impacted by the implementation of these laws. For instance, national goals for phosphorus recovery for recycling from sewage exist in both Germany and Sweden.

For example, in Sweden, productive soil receives back around 60% of the phosphorus that was previously present in wastewater [108–110]. Therefore, to adapt to satisfy this need, proper modification is essential. In the same vein, P-recovery was declared to require legal requirements by Germany in 2017 and Switzerland in 2016. An additional objective of 50% phosphorus recovery from sewage has been suggested by the environmental authority of Å land, an autonomous province of Finland [111]. One EU law that will facilitate a quicker shift to wastewater nutrient recovery is the fertilizer regulation (EC 2003/2003).

Some of the environmental regulations include

(i) Protection of the environment, and in particular of the soil, when sewage sludge is used

(ii) Threshold values for land application of organic recycled matter

(iii) Amount of biodegradable municipal waste for landfill

(iv) Priority order in waste prevention and management legislation and policy

It's interesting to note that several nations—particularly Sweden and the Netherlands—have embraced this policy. This suggests that technology and the kinds of recovered products are also impacted by legislation. Sweden and Germany, for example, both declared their national targets for recovering phosphorus. While the German Federal Environment Ministry (UBA) is focused on recovery for recycling in sewage works, Sweden is aiming to use recovered P in farming produced from sewage sludge. It's also important to remember that different nations and areas have distinct recovery drivers. For instance, the recyclable product at Thermophos Treatment Facilities (Holland) must be calcium phosphate or aluminium phosphate rather than phosphorus recovered as struvite.

Therefore, it follows that the person who decides what characteristics of the product need to be retrieved and produced is the industrialist, end-user, politician, etc. Knowing which actor determines the kind of product that is reached in recovery is therefore crucial. When a certain product is requested by the industry, technology is produced to meet those needs. Politicians, on the other hand, may have more options when determining the guidelines for rehabilitation.

Socio-Cultural Challenges of Nutrient Recovery and its Management

Nutrient recovery is being hampered by these prejudiced notions and ethical, social, cultural, and religious views. Positive attitudes encourage the adoption and advancement of technology as well as the use of recovered goods. But a bad impression puts an end to it. Prejudices based on culture and religion, for instance, have an impact on farmers' acceptance of fertilizer made of faeces. For example, there is very little chance that a farmer will be open to considering the advantages of utilizing fertilizer derived from faecal sludge if the farmer feels that using such fertilizer is against religious and cultural norms.

Results of a study by Cofie et al. [112] showed that cultural and religious views opposing the use of fertilizers based on faeces have a detrimental effect. Many elements must be taken into account to manage the socio-cultural issues associated with nutrient recovery. In addition to the health risks linked to the use of human excreta in farming, which are successfully resolved through composting [112-115], reasonable costs and a strong marketing plan may persuade people to change their minds. According to Rouse et al. (128), successful marketing was responsible for the compost project's success in Horizon Lanka, the institution, and the community in Sri Lanka. According to a study by Drescher et al. [116] on profitable composting businesses in four Asian nations (Pakistan, Sri Lanka, India, and Bangladesh), identifying the target market niche and having a solid marketing plan are vital. According to Cofie et al. [112], if faecal sludge-based fertilizers (FortiferTM) are less expensive than alternative fertilizer products and are simpler to handle and transport than other organic fertilizers, farmers' propensity to buy them may be influenced by the price factor.

According to Ali [117], the problem with the majority of compost operations is a weak marketing plan. Additional characteristics that affect farmers' decisions to purchase fertilizer in various regions (Ghana, Kampala, Kunnegala, Hanoi, and Bangalore) were also found to be significant in the study conducted by Cofie et al. [112]. An appropriate credit offer was ranked as the most crucial product feature in several of the research regions. Some people view it as a convenient place to purchase the product, while others base their decisions to purchase fertilizer on the nutrient content and application techniques of the various goods.

Additionally, some farmers base their decisions about which fertilizer to buy on a variety of characteristics, including organic matter, water-holding capacity, volume to apply, and a label indicating product certification by pertinent authorities like the Ministry of Food and Agriculture. It's funny how some people are only convinced to buy fertilizer if they know someone who has used and tested the product. This is the most crucial factor to consider. Farmers find it challenging to switch to compost despite the high expense of inorganic fertilizer because they believe compost will provide increased production benefits over time. The farmer's position may change if additional advantages of recovered nutrients are emphasized. These advantages include the ability to increase agricultural productivity, crop nutrient availability, and long-term soil fertility. They may also improve sanitation and environmental sustainability.

- **Ecological - Environmental Challenges of Nutrient Recovery and its Management**

The term "environmental challenge" mostly refers to soil recycling and sanitation. Environmental and public health protection are two reasons why this behaviour is objectionable. Numerous investigators have carried out investigations to determine the appropriateness and potential health hazards linked to the utilization of human excreta as a source of nutrients in agriculture throughout different regions of the world, such as Ghana, Vietnam, Uganda, and so on [111,118-119]. The ultimate aim of wastewater nutrient recovery is the production of fertilizer suitable for agricultural use. The application and use of sewage sludge (biosolids) in agriculture is a significant problem for the nutrient recovery sector. High-purity biosolids typically face the following issues: Low purity (i) Low plant availability of nutrients (ii) High water content and low nutrient content

A review of the literature was done by Kasurinen et al. [120] regarding the presence of various organic compounds in Finland's municipal sludge. Numerous hazardous organic pollutants, such as polychlorinated biphenyls, polyaromatic hydrocarbons, polybrominated diphenylethers, and perfluorooctane sulfonate, were found to be present in the sludge. Sludge that may readily seep into the earth and subterranean aquifers was also found to contain pharmaceuticals and a few personal care items (triclosan, citralopram, and diclofenac). Certain hazardous organic compounds (triclosan and phatalates) were found to be highly persistent in both the sludge and the sludge-amended soil at high concentrations, according to a study by Fjäder [121] on the occurrence of harmful substances in dried sludge and the accumulation in sludge amended soils. It has also been discovered that PFAS and PBDE chemicals build up in earthworms.

According to the EU report SCOPE [109], using sewage sludge for agriculture is the most cost-effective and environmentally friendly option. An improvement in sludge quality and public confidence will have a significant impact on the development of sludge application in agriculture. Agriculture uses fifty-five per cent of the entire amount of sludge produced, according to Lewis and Gattie [122]. The nutrient recovery business will benefit greatly from studies and projects that investigate the feasibility of creating sludge with high nutritional content and no hazardous materials suited for agriculture. Among these initiatives are the REVAQ project in Sweden, which brings together the public, consumers, farmers' organizations, food businesses, sewage and water utilities, and commerce. Another is BIOWASTE, which investigates the safe recycling of sewage sludge on agricultural land through bioprocessing. Five partners from four EU nations—Denmark, France, Greece, and Spain—are involved. Vivendi Water Systems developed SAPHYR, a novel chemical stabilization process based on the acidification of biosolids combined with nitrite addition [123–124].

- **Economical (Financial) Challenges of Nutrient Recovery and its Management**

This effort has proved the technological feasibility of nutrient recovery from wastewater. Nonetheless, is nutrient recovery economically feasible? Is a crucial concern for nutrient recovery adoption. To fully assess a nutrient recovery technology, a thorough analysis of the methods' economics is necessary. This is a challenging undertaking to do, nonetheless, as the majority of recovery techniques have not yet reached their full potential and the government and farm groups have not yet fully confirmed the recovered products' acceptance. Therefore, it is challenging to estimate the cost of a technological operation related to nutrient recovery. The price of different recovery systems does not account for savings on sludge handling or wastewater treatment plant operating expenses, nor does it account for revenue from fertilizer sales. Most of the time, the financial advantages of resource-saving through waste-derived nutrients are not acknowledged. When compared to the cheap market price of fertilizers made from phosphate rocks, the economic viability of nutrient recovery technology appears to be questionable. The cost of recovery technology today is significantly more than the cost of phosphate rock (measured in euros per tonne P). This is a little unclear because nutrient recovery technology typically doesn't offer any new operational advantages or a product that can be sold right away. This is not meant to be an exhaustive treatment of the economics of phosphorus recovery.

However, if operational cost savings are taken into account, simple economic considerations demonstrate that nutrient recovery is viable. Furthermore, when analysing the economics of nutrient recovery technologies, it is crucial to take into account the increased recovery rates and extra operational benefits [125, 127]. It's critical to keep in mind the advantages nutrient recovery offers the ecosystem. For example, recovering phosphorus from wastewater enhances the availability of a non-renewable resource and stops eutrophication in the receiving environment. Costings for internal effects as well as environmental advantages should therefore be completed for the full economic viability of nutrient recovery technology [126]. Since they are determined by the market, internal expenses, which include operational and maintenance costs directly related to the project, can be clearly expressed in monetary terms. The non-economic or monetary benefits, consequences, or impacts of the technology are known as the environmental benefits, or positive externalities in the language of economics. Due to their lack of market value, they are typically not valued in money [125]. The majority of traditional approaches now in use for evaluating the economic viability of recovery programs only take into account internal effects, devaluing exterior benefits to a list of benefits that lack any financial measurement. As a result, many projects' appraisal and evaluation of their actual costs are inadequate. Results indicate that these kinds of projects are not financially feasible when a healing process is examined just in terms of internal effects. However, when the external advantages are taken into account alongside the internal effects, the process's economic viability is determined. Therefore, as long as the benefits to the environment are taken into account, nutrient recovery is a financially viable technique.

Conclusion

Globally, there is a growing need for mineral fertilizers due to the reckless disposal of vast amounts of organic waste, which pollutes the environment. A good step towards closing the nutrient cycle gap between modern human society and future scarcity of non-renewable nutrients and fossil-based fertilizers is the development of new processes and technologies and strengthening of existing ones to recover and re-use nutrients from both solid and liquid wastes as well as evaluation of their relative agronomic efficiency. In conclusion, the technological, environmental, health, ecological, sociocultural, and economic aspects are crucial areas that should be taken into consideration while handling the issues of resource recovery from the aqua system.

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