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REVIEW

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Waste to Worth: Nutrient Recovery Strategies from Wastewater

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Conflict of Interest

The authors declare that the manuscript was formulated in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Authors Contribution

All authors listed have made a substantial, direct, and intellectual contribution to the work, and approved it for publication.

Abstract

This article explores the potential of wastewater as a valuable source for nutrient recovery. Wastewater has been investigated as a source of nutrient recovery for two reasons. Firstly, it contains high concentration of nutrients. Secondly, it exists in large quantities. Recognizing this potential, researchers have increasingly turned their attention to the recovery of nutrients from wastewater. The recovery of nutrients from wastewater serves a dual purpose. Firstly, it addresses the environmental concerns associated with the high concentrations of nutrients present in wastewater. Secondly, the large quantities of wastewater offer a substantial resource for nutrient reclamation. Minimizing the environmental footprint of wastewater treatment becomes achievable through nutrient recovery, simultaneously addressing the crucial issue of nutrient depletion in soil. The recovered nutrients, once reclaimed, can be seamlessly integrated into fertilizer production, contributing to agricultural practices and ensuring food security. This article delves into the advancements, challenges, and the overarching significance of nutrient recovery from wastewater in the pursuit of sustainable and integrated waste management practices.

KEYWORDS

Nutrient recovery, nitrogen recovery, phosphorus recovery, wastewater treatment, circular economy, energy

INTRODUCTION

The process of nutrient recovery involves reclaiming valuable elements, such as nitrogen and phosphorus, from wastewater that would otherwise be disposed of. These recovered nutrients arethen transformed into an environment friendly fertilizer, serving both ecological and agricultural needs. Wastewater treatment is not adequate to meet sustainability. This is because wastewater treatment focusses only at releasing the treated water at the prescribed standard levelsof nutrients. Whereas nutrient recovery from wastewater is an advanced option for a self-reliant and sustainable circular economy. Nitrogen and phosphorus are present at high concentrations in Wastewater. During the process of wastewater treatment, nitrogen is oxidized to nitrate followed by denitrification to release the N2 gas into atmosphere while phosphorus is accumulated in the sludge. Hence, nutrients are not being utilized during wastewater treatment. But in nutrient recovery process, such nutrients can be recovered and put into use (Yamashita and Yamamoto-Ikemoto, 2014)

WHY NUTRIENT RECOVERY HAS BECOME A NECESSITY?

- Phosphate is a non -renewable resource. Recovery of wasted P is critical considering thediminishing phosphorus resources and growing demand for fertilizer.
- Production of nitrogen fertilizer is energy intensive. So, recovery of N from wastewater streams would be an energy-efficient alternative to the manufacture of fertilizer from atmospheric nitrogen.
- Discharge of these nutrients through treated wastewater causes eutrophication in the receiving waters.
- Majority of wastewater are neither collected nor treated. Wastewater is a potential resource,but it is often seen as a burden to be disposed of. In India, the potential of wastewater is scarcely explored.

Advantages of implementing nutrient recovery from wastewater

Implementing nutrient recovery from wastewater offers several key advantages, contributing toboth environmental sustainability and economic efficiency:

1. Resource Conservation: Nutrient recovery minimizes the wasteful disposal of valuable resources present in wastewater, such as nitrogen and phosphorus. Instead of being treatedas pollutants, these nutrients can be reclaimed and repurposed for beneficial applications.
2. Environmental Protection: By preventing the release of excess nutrients into water bodies, nutrient recovery helps mitigate the harmful effects of nutrient pollution. This, in turn, safeguards aquatic ecosystems, preventing issues like algal blooms and oxygen depletion that can negatively impact aquatic life.
3. Sustainable Agriculture: The recovered nutrients can be converted into eco-friendly fertilizers. These fertilizers provide a sustainable source of essential nutrients for crops, promoting healthier and more productive agricultural practices. This sustainable approach reduces the dependence on traditional, energy-intensive fertilizer production methods.
4. Circular Economy Contribution: The concept of nutrient recovery adheres to the principlesof a circular economy, facilitating the closure of the nutrient loop. Instead of the traditional linear economy which follows "take, make, dispose" model, this approach embraces a circular flow, where nutrients are recycled

and reused, reducing the overall environmental impact (Vinayagam et al., 2023)

5. Economic Opportunities: The recovered nutrients, now transformed into fertilizers, present economic opportunities for industries involved in nutrient recovery. This creates a new market for environmentally friendly fertilizers thereby reducing imports of biofertilizers and fostering innovation and economic growth within the wastewater treatment sector.
6. Energy Savings and emission reduction: Nutrient recovery processes, such as ion exchange and adsorption, can be designed to be energy-efficient. This contributes to overall energy savings within wastewater treatment plants, making the entire process more sustainable and cost-effective.

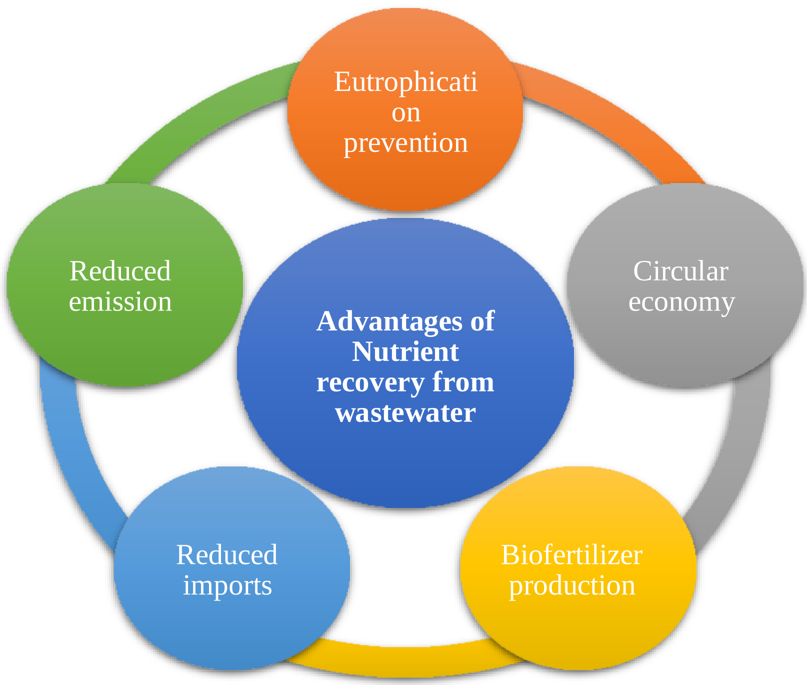

Fig 1: Advantages of nutrient recovery from wastewater

How nutrient recovery can be done?

The process of nutrient recovery from wastewater can be in three steps. These are nutrient accumulation, nutrient release and nutrient extraction.

Techniques used for nutrient recovery

I. Indirect recovery of nutrients
1. Ion exchange / adsorption
2. Chemical precipitation
3. Electrodialysis

Each of the above technique is followed by:

I. Gas stripping
II. Absorption to acid

II. Direct recovery of nutrients
1.Gas permeable membranes / membrane filtration
2. Struvite precipitation
3.Membrane filtration
4. Algae accumulation

METHODS OF NITROGEN RECOVERY

Indirect recovery methods

1. **Ion exchange and adsorption**

- Reactive nitrogen primarily exists as NH^+ unde$_4$r typical wastewater pH conditions. Due to its cationic nature, processes based on ion exchange and adsorption become highly relevant.
- Zeolite stands out as the most popular ion exchanger and adsorbent for nitrogen recovery. Its efficiency, economic competitiveness, and operational simplicity make it a preferred choice. Natural zeolites exhibit ammonium adsorption capacities ranging from 3.11 to13.73 mg/g (Nazari, 2017). To recover nitrogen from the saturated zeolites, a two-step process involving gas stripping and adsorption into an acid solution is implemented.

2. **Electrodialysis**

In this, anions and cations are separated in presence of an electric field. Positively charged species such as K^+ and $NH4^+$ migrate towards the cathode by passing cation-exchange membranes (CEM), which selectively permit only cationic species. Hence, ammonia is concentrated in the cathodic side of electrodialysis cell (Zhang et al., 2019). Ammonia recovery requires subsequent stripping and absorption into an acid solution.

3. **Bio-electrochemical system (BES)**

Within bio-electrochemical Systems (BES), specific microorganisms directly convert the chemical energy present in organic matter into electrical energy (Pant et al., 2012). In case of ammonium recovery, organic matter in wastewater is oxidized at anode by the bacteria. The ammonium ions so formed, are transported to the cathode chamber. The high pH at cathode, allows for recovery as ammonia. Anode and cathode chambers are separated by an ion exchange membrane to prevent mixing of the oxidation and reduction products (Kuntke et al., 2018). BES is potentially a sustainable way of treating wastewater as it produces electricity and recoversammonia while utilizing low-grade substances such as wastewater itself as an electron source.

Gas stripping and acid absorption

In the final step of nutrient recovery, gas stripping and acid absorption play is done. Gas strippingi s a pH-dependent process i.e, at a pH of approximately 9.3, ammonium nitrogen from the solutionconverts into ammonia gas (Serna-Maza et al., 2014). Following gas stripping, the ammonia is absorbed into an acid solutionto lower the pH, completing the nutrient recovery process.

Direct recovery of nitrogen

1. **Struvite precipitation**

Struvite precipitation, involving the formation of $MgNH_4PO_4 \cdot 6H_2O$, is a key process in nutrient recovery. In this process, the ammonium ions in effluent gets involved in struvite formation and hence gets precipitated. The optimal pH range for struvite precipitation falls between 7.5 and 9.0 (Krishnamoorthy et al., 2021).To facilitate struvite formation, equimolar amounts of Mg^{2+}, NH_4^+, and PO_4^{3-} are essential. Hence,magnesium (Mg^{2+}) is added to the effluent. Simultaneously, alkali is also introduced to maintain the pH within the suitable range for struvite precipitation. Consequently, the costs associated withstruvite precipitation are strongly influenced by the choice of magnesium and alkali sources employed in the process.

2. **Algae accumulation**

Autotrophic organisms such as microalgae can remove nitrogen via assimilation for biomass growth without oxygen consumption. While the process is still in the developmental stage, the application of microalgae for wastewater treatment is typically conducted in open raceway ponds. This choice is influenced by the lower capital costs associated with open raceway ponds when compared to photobioreactors. Anadvantage of employing microalgae in wastewater treatment is their capability to enhance the quality of biogas generated during anaerobic processes. However, a notable disadvantage is the poor settling properties of microalgae, leading to increased operating costs associated with their harvesting and dewatering.

Gas permeable membranes (GPMs)

Gas permeable membranes (GPMs) offer an efficient solution for ammonia recovery, with the capability to reclaim 95% of ammonia (Soto-Herranz et al., 2022). In this system, high-strength wastewater containing ammonia is treated by recirculating H_2SO_4 through tubular membranes submerged in the wastewater. As a result, NH_3 is recovered in the form of $(NH_4)_2SO_4$. While GPMs are highly effective for high-strength wastewater, it is worth noting that this method may not be economicallyviable for situations where the ammonia concentration is less than 50 mg/l.

Methods of phosphorus recovery

Indirect methods of P recovery

1. **Ion exchange and adsorption**

Unwanted ionic contaminants are eliminated from water by exchanging with ions present in media. In ion exchange for phosphorus accumulation, P-selective media is used (Pismenskaya et al.,2022). The PO is adsorbed into this media by ion exchange. Ferric and Aluminum hydroxides are the common adsorbents used due to their ability to form ligands with phosphates.

2. **Electrodialysis**

The process involves the separation of anions and cations in the presence of an electric field. Anions move towards the anode, passing through anion exchange membranes that selectively permit the passage of negatively charged species (Dudeja et al., 2024).

3. **Biological P recovery**

EBPR stands for enhanced biological phosphorus removal process. EBPR process is based on accumulation of phosphorus by phosphate-accumulating organisms (PAOs). Thisresults in enrichment of phosphorus in sludge. EBPR process remove as much as 80-90 % of phosphorus (Zheng et al, 2014).

Direct methods of P recovery

Struvite precipitation

Struvite precipitation facilitates the recovery of phosphorus in a manner similar to nitrogen recovery. Here phosphorus is recovered through formation of struvite.

1. **Algae accumulation**

Autotrophic organisms such as microalgae can remove phosphorus too, via assimilation for biomass growth without oxygen consumption.

2. **Membrane filtration**

Membrane filtration has the added benefit of collecting dissolved as well as solid phosphorus, drastically improving phosphorus removal. Microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO) are all membrane processes which selectively separate constituents from waste. Nutrients in particulate form >0.1 µm in size (suitable for MF or UF) or in soluble form (suitablefor NF or RO) can be selectively removed.

CONCLUSION

Struvite precipitation, in particular, has gained significant attention due to its efficiency in recovering both nitrogen and phosphorus. In summary, the advantages of implementing nutrient recovery from wastewater extend beyond environmental benefits to encompass economic, agricultural, and societal advantages. By turning wastewater into a valuable resource, this approachcontributes to a more sustainable and resilient future.

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