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Current scenario and challenges in recycling of human urine generated at source in rail coaches as resource

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Abstract

The current scenario of human urine being directly discharged into the environment without recycling, despite being an economical source of fertilizer. Train coaches are the major source of large-scale urine waste generation. Adopting a circular economy creates significant synergies toward usages of water generated after nutrient recovery from urine. Some advanced decentralized treatment systems, such as electrochemical, bioelectrical, or reverse osmosis, would be useful to treat and recover nutrients from urine waste/wastewater. The laborious and costly affair of removing nutrients like N, P, and K from human urine needed a sustainable solution. These recovered nutrients can be reused as fertilizers in irrigation and, indirectly, in large-scale biodiesel production by being used in microalgae cultivation. However, the potential of reusing human urine waste is yet to be explored commercially. Additionally, artificial intelligence may be explored with sustainable approaches for urine separation and recycling soon.

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Human waste, Waste to value, Onboard management, Bio-fertilizer, Decentralization, Policy for management.

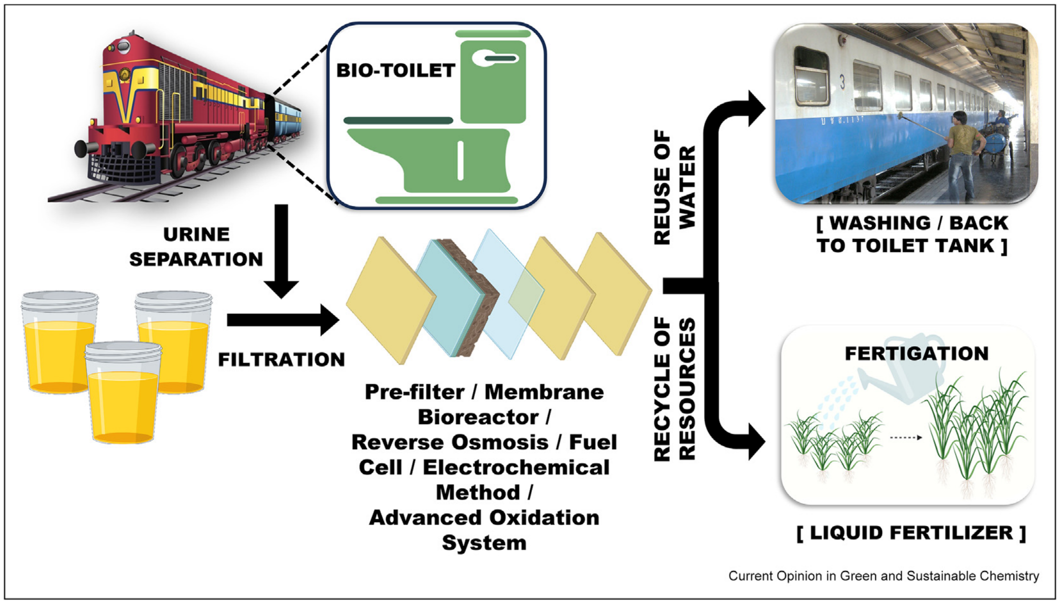
Introduction

When wastewater is discharged into water bodies, nutrients like nitrogen and phosphorus are introduced, which causes harmful algal blooms, fish kills, and other ecological problems. By reusing treated wastewater instead of discharging it, these nutrients can be captured and reused as a resource rather than being wasted or causing harm to the environment [1,2*]. Additionally, treating and reusing wastewater can help to conserve freshwater resources, reduce energy use and greenhouse gas emissions, and provide a reliable source of water for non-potable uses like irrigation, industrial processes, and toilet flushing [3,4**] (Figure 1).

The Indian Railway system stretches almost 86,000 km and operates the world's most densely utilized train system, with a daily passenger count of 24 million, leading to the daily discharge of a large amount of human organic waste. Data show nearly 40,000 tons of human excreta is dumped daily directly into the ground and onto the railroad tracks in the coaches. Its long decomposition time and contaminated water under bridges spread diseases like dysentery, vomiting, diarrhea, typhoid, dengue, and malaria [5]. The issue of open discharge is resolved nowadays by installing Bio-Toilets. "Bio-Toilets are the vacuum composting toilets fitted in the rail coaches that use microorganisms under aerobic or anaerobic conditions to treat human waste by biological decomposition process for further use as agro fertilizers." It conserves energy and reduces water and air pollution. A multi-directional strategy has been implemented to adopt environment-friendly toilets on Indian Railway passenger coaches [6].

This article deals with source-separated urine waste, processing liquid fertilizers on board, and then collecting these fertilizers at terminal train stations for widespread usage in agriculture [7]. The composition of human urine is elemental nitrogen (8.1–9.2 g/L), phosphorus (8.1–9.2 g/L), and trace amounts of boron, zinc, copper, iron, cobalt, and manganese [8]. In typical

Figure 1



Showing schematic representation of technologies to recover resources from human urine collected from rail coaches.

centralized wastewater treatment systems, nitrogen and phosphorus are collected partially in a reusable form [9]. Instead of sending urine to centralized wastewater treatment plants, urine may now be separated from solid waste for nutrient recovery due to the invention of dry toilets lowering their treatment load [10,11]. The primary nutrients (N, P, and K) are in water-soluble ionic form in source-separated human urine, making them readily available for plant uptake [12,13*].

Though high nutrient content is available in human urine, its direct use as fertilizer is prohibited due to environmental, hygienic, and social issues. To overcome these limitations, magnesium (Mg) is externally added to precipitate the nutrients, creating struvite, a fertilizer with a slow release rate [14]. Significant synergy could be seen for reusing waste (human urine) into resources to accelerate the circular economy of water and the implementation of Industry 4.0 (using artificial intelligence to regulate the recovery of nutrients from urine and using the same as fertilizers in agriculture) [11]. The present article focused on the challenges of using aqueous waste in the economy.

Evolution to circular economy

The circular economy is a concept that aims to shift from a traditional linear economic model of “take, make, use, and dispose” to a more regenerative and restorative approach. It seeks to keep materials and resources in use for as long as possible, reducing waste and pollution and promoting sustainable production and consumption patterns [15**].

In water scarcity, the circular economy can be crucial in optimizing water management and reducing the water footprint. Adopting circular practices, such as water reuse, recycling, and recovery, decreases freshwater demand, increases water efficiency, and reduces environmental impact [16]. For instance, the circular economy approach in agriculture involves wastewater usage for irrigation and nutrient recovery from waste streams. Industrial processes involve water-efficient technologies and closed-loop systems [17]. Overall, the circular economy can provide an effective solution to address the challenges of water scarcity and resource depletion while promoting sustainable development and economic growth. The circular economy is defined by the interaction with sustainable and resource-efficient practices. Overall viability is always a key issue with the circular economy. Public perception toward water usage generated after urine treatment has different safety and regulatory challenges. The recycling and reuse strategy is always good for better managing waste, while the circular economy also boosts its cost-effectiveness and acceptability [15**,16].

The main disadvantage of the current traditional procedures is that only a single nutrient element may be recovered at a time. The base of the entire idea is the utilization of collected and processed human urine (N,

Table 1

Microalgal culture with diluted human urine and nutrient recovery.

Micro-algae	Culture mode	Urine Dilution	Nutrients recovered	Ref.
Scenedesmus acuminatus	Semi-continuous mode	1:20	52 % N, 38 % P	[23]
Chlorella sorokiniana	Continuous mode	1:3	36 % N, 100 % P	[24]
Arthrospira platensis	Semi-continuous mode	1:10	58.43 % protein, 10.67 % lipids	[25]
Spirulina platensis	Continuous mode	1:120	97 % NH_4^+-N, 96.5 % P, 85−98 % of urea	[26]
Chlorella vulgaris	Lab-scale membrane photobioreactor (MPBR) system	1:30	77.3 % N, 53.2 % P	[45]
Local mixed culture microalgae	Autotrophic microalgae cultivation	1:20	90 % N, 58 % P, 23 % lipid	[46]
Native microalgal consortium	Central composite rotatable design	1:10	26.3 % lipid	[47]
Chlorella sorokiniana	Batch culture	Undiluted	80.4 % N, 96.6 % P	[48]

P, and K) from rail coaches as nutrients to culture microalgae at a larger scale (Table 1) [8].

Waste to value

Wasting human urine or its conventional management in the wastewater treatment plant uses large amounts of energy and reduces nutrients (phosphorus and nitrogen) through waste dispensing [18,19**]. As an outcome, a separate pool of urine is an inventive substitute for sewage management. Such as no-mix technology is a technique that produces source-separated urine comprised of inorganic salts (e.g., Ca^{2+} and Mg^{2+}), urea, and water. It is an encouraging but underutilized supply of N and P fertilizers in agriculture [20]. Therefore, using source separation human urine minimizes environmental effects during a fertilizer's life cycle.

Bio-Toilets are installed with the facility; they do not have to collect solid and liquid waste separately. The urine collection chambers are connected to an exit pipe that opens upon a minimum threshold volume (e.g., 5 L or 10 L). Then, outlet chambers equipped with experimentation designs process the influent urine from the rail coaches and transfer it to the last bogey specially designed for the same. A chamber, roughly the size of a rail coach, is designed to collect all the wastes, either processed or to be processed further at the end of the train. This liquid waste can be recovered at the terminal station for further treatment and use. Instead of conventional methods for nutrient recovery (liquid biofertilizer), we should think about the biological process through which we can produce biofuels, high-value chemical products, and nutraceuticals [21*,22]. Microalgae or microphytes are the phytoplanktons that grow in freshwater, marine aqua systems, and hypersaline environments [23]. It is a unicellular algal species that contain high potential in industrial applications. Different studies show that microalgae such as *Chlorella*, *Arthrospira*, and *Scenedesmus* can be grown and harvested using source-separated urine (Table 1) at various dilution ratios in the range of 1:1−1:180 [8,24−26]. Using urine as a nutrient source to grow microalgae is realistic and cost-effective as it contains significant nutrients essential for microalgal growth. However, the high concentration of ammonia in urine can be toxic to microalgae; therefore, proper dilution is necessary to reduce ammonia toxicity [27].

Scientist reported that diluting urine to an optimum concentration supports microalgae growth and boost their productivity. Furthermore, using urine as a nutrient source for microalgae cultivation is an attractive approach for sustainable wastewater treatment and resource recovery [24,25*]. In addition to providing a sustainable and cost-effective source of nutrients for microalgal cultivation, urine also offers the potential for producing high-value products, such as biofuel, biofertilizers, and animal feed supplements.

Energy-efficient recovery of resources

The recovery of liquid fertilizer (useful in foliage spray) does not require energy like the Haber-Bosch process [28]. It is estimated that 15−20% of global requirements could meet from this source-separated urine. Urine is rich in other nutrients needed for plant growth, making urine an acceptable plant fertilizer [29]. On-site urine separation is a concern, and toilet design must be altered to isolate urine and feces separately dealing with trains and ships. In general, human urine does not contain pathogens which will have risks. The most common method to treat urine is prolonged storage at 4−20 °C in storage tanks. WHO suggested one month withholding period between fertilization and collection. During storage, the pH of urine increases due to the breakdown of urea into ammonia and hydrocarbonate, which destroys pathogens over time [29,30**]. Additionally, high temperature and time itself can enhance the pathogen-killing effect.

The present-day situation calls for efficient alternatives that reduce the water footprint and resource optimization. Although chemical-based fertilizers increase crop yield, overdoing them has detrimental environmental concerns. Henceforth, fertilizer, critical for sustainable agriculture, is needed [20,31]. Thus, sustainable agriculture practices have been developed to reduce the reliance on chemical fertilizers and promote more efficient use of nutrients.

Bottlenecks in separation for human urine in on-board transport

Earlier, the hopper toilet system, a drop chute toilet, was commonly used in trains which works by allowing the waste to drop through a hole in the floor of the train car onto the tracks below. This method was not only unsanitary but also posed an environmental hazard. Modern trains are equipped with more advanced waste management systems designed to collect and dispose of human waste safely and environmentally friendly. However, some older rolling stock, particularly in less developed regions of the world, may still use the hopper toilet system due to the cost and technical limitations of installing more advanced systems. Designing for low or no waste in water treatment can involve multiple strategies, including:

By-product utilization

Using by-products to power the water treatment process creates a circular economy where waste is minimized, and resources are optimized. For example, biogas produced during the anaerobic digestion of sludge can be used as fuel to generate electricity or heat for treatment [17,32,33].

Smart water treatment technology

Implementing real-time, automated processes and advanced analytics enable operators to monitor water quality parameters and adjust treatment processes accordingly, ensuring that only the necessary amount of chemicals and energy is used. Additionally, smart water meters can help reduce water waste by identifying leaks and enabling quick repairs.

Closed-loop systems

Closed-loop systems involve reusing treated water and recovering resources such as nutrients and energy from wastewater and, thus, reduce their reliance on external resources and minimize waste [34**,35**].

Role of artificial intelligence and machine learning in source separation

Machine learning algorithms would be useful to analyze all inputs (volume of urine, dilution rate, etc.) for better utilization of energy and reagents used in the procedure. These algorithms can be used to ensure that the target quality standards are met at all times while minimizing the use of resources. The supervisory control and data acquisition (SCADA) system will use the output to update the operating set points automatically [36]. This approach, known as closed-loop control, is becoming increasingly popular in the chemical industry. Alternatively, the algorithms can be used to provide decision support to the operators, which helps operators for better decisions, reduce the risk of errors, and improve the efficiency of the process. Overall, the use of machine learning algorithms and decision support system (DSS) in the chemical industry is helping to improve the quality of products, reduce waste, and minimize the environmental impact of chemical processes [37].

Challenges

Trains and other on-board transport should adopt environmental sustainability and actions to support a circular economy.

a. **Infrastructure:** Significant investments are needed to retrofit existing rail coaches or design new ones to accommodate urine recycling systems.
b. **Health and safety issues:** Due to pathogens and other contaminants in urine, urine recycling systems must ensure that the recycled water is safe for human use [38].
c. **Technical limitations:** Due to limited space and power supply, existing urine recycling technologies are complex and energy-intensive for rail coaches. They also require regular maintenance and monitoring, the biggest challenge [34].

Future perceptions and recommendations

There are ongoing efforts to develop more efficient, cost-effective, and scalable technologies for recycling human urine. This includes developing membrane-based and electrochemical urine treatment systems and other innovative solutions [39**-42*]. Cost-effective filtration to recover nutrients utilized as biofertilizer may be used in developing countries with limited resources, such as gravity-driven [43] or electropositive membrane filtration [44], with low-resource dependency and longer membrane lifetime. Using artificial intelligence to regulate urine recycling technology is a comprehensive and promising approach, which may be utilized for large-scale production and improved quality products in the near future.

Submission declaration

The corresponding author, on behalf of all co-authors, declares that we have read and agreed to the submission guidelines of the journal, and I confirm that I shall bear the complete responsibility for submission. I declare that all the authors listed contributed significantly to the manuscript. I confirm the legitimacy of the manuscript, and it is not plagiarized. I hereby confirm that I will not submit the manuscript elsewhere until the decision is made by the editors of this journal.

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Not applicable.

Authors' contributions

KKD: designed, edited, and conceptualized the manuscript; DR, AK, AB, AY, VK: editing and reviews; SR: prepared first draft; and YKM: editing, reviews, and final draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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