

## Review

## Challenges and opportunities of nutrient recovery from human urine using biochar for fertilizer applications



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## ABSTRACT

Although urine constitutes less than 1% volume of the total wastewater, it adds up 50–80% of the nutrient load [Phosphates ( $\text{PO}_4^{3-}$ ) and Nitrates ( $\text{NO}_3^-$ ), Ammonium ( $\text{NH}_4^+$ )] in wastewater treatment plants (WWTPs). Recovery of Phosphorous (P) and Nitrogen (N) from urine diminishes the eutrophication impact as well it could act as a sustainable source of P by lessening dependence on finite phosphorite reservoirs. Due to its environmental (carbon-negative process) and economic (produced from waste) value, biochar is gaining the researcher's attention in recent years. Many studies are ongoing to introduce novel structures and modifications in the surface properties of biochar for efficient adsorption of P and N. Direct application of urine as fertilizer has been discouraged due to various hygienic pitfalls further forced to explore the alternative nutrient recovery methods. This review article explores the nutrient recovery paradigms from source-separated human urine for abridging the nutrient gap between wastewater treatment and agricultural productivity using pristine/engineered biochar. The influencing factors for P and N's adsorption process by biochar and its detailed mechanisms have been outlined. Further, it deliberates the possible strategies of engineering the biochar to enhance the recovery of P and N from human urine. Applications of nutrient-loaded biochar in an agricultural field could act as a slow-release fertilizer to releases P and N in addition to soil conditioning. This review emphasized the challenges of storage, transportation, contamination of urine, and possible difficulties in the adsorption process by pristine/engineered biochar.

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## 1. Introduction

A potential crisis of limited phosphorite reserve and increasing demand in the fertilizer industry caused by population explosion has encouraged the researchers to recover phosphorus from wastewater (Desmidt et al., 2015). Direct application of nitrogenous fertilizer is a dominant source of anthropogenic ammonia (NH<sub>3</sub>) emissions, resulting in the formation of secondary aerosols, eutrophication of water bodies, and destructions of biodiversity in a terrestrial ecosystem. This situation warrants an immediate and suitable alternative for these inorganic based fertilizers on current agricultural practices.

Sfez et al. (2019) discussed the paradigm shift from linear to a circular economy in accessing the sustainability of products obtained from household wastewater. Ecological Sanitation (EcoSan) is a holistic approach to closing the gap between sanitation and agriculture. EcoSan system aimed to complete the water cycle with the minimum expense on materials and energy to contribute to an economical and sustainably sound sanitation system. Though urine could be a potential cheap substitute for chemical fertilizers, direct application on the agricultural fields was discouraged due to various problems associated with it. A considerable volume of urine with relatively low concentrations of plant nutrients and large space requirements and long duration (~1–6 months) for sanitization and product acceptability by consumers halts the direct applications as fertilizer. However, the discharge of urine in the modern sewerage systems adds up an additional 80% N, 60% K, and 50% P load to WWTPs. Yet, urine has the numerous macronutrients needed for plant growth (Diaz-Elsayed et al., 2019); moreover, urine excreted from a healthy individual lacks toxic compounds that increase its application farming activities (Ganrot et al., 2007). However, due to extensive use of xenobiotics, poisonous compounds such as pharmaceuticals and personal care products (PPCPs), and endocrine-disrupting compounds (EDCs) could also contaminate urine, and plants might accumulate that with the application of urine (Worley et al., 2017). When consumed, these toxic compounds could possess serious health hazards to humans and animals.

Nevertheless, technically viable, economically feasible, and socially acceptable nutrient recovery methods need to develop for the sustainable application of urine in agricultural practices. Utilization of urine for recovering nutrients lessens the dependence on the nonrenewable phosphorous source (Wielemaker et al., 2018) and further preserves the water ecosystem from the impacts of eutrophication. Recovery of phosphorus and nitrogen from urine could change the notion of being pollutants of wastewater and can be deemed resources of phosphorous and nitrogen industry, especially in the agricultural fertilizer sector.

Although numerous methods were documented in the literature

for the recovery and removal of P and N from wastewater; especially from urine, most of the methods have been executed at the lab-scale. Only very few have been implemented at the industrial scale. Chemical precipitation (Kabdaşlı et al., 2018), biological nutrient recovery methods, struvite precipitation (Wei et al., 2018), ion exchange (Hedstrom et al., 2006), air stripping (Wei et al., 2018), construction of wetlands (Luo et al., 2018), electrodialysis (Wang et al., 2017), membrane separation (Zhang et al., 2014) and sorption (Kabdaşlı et al., 2018) are some of the prominent and commonly used techniques for the recovery and removal of nutrients from urine. All methods have their own merits and demerits in terms of effectiveness at low phosphorus concentration, generation of waste sludge, use of chemicals, high capital, and energy cost. Out of these, the sorption technique provides a promising treatment option because of convenience, simple operation, cost-effective sorbents, feasible reactor designs and economics (Bhatnagar and Sillanpaa, 2011). Sorption procedure is relatively more effective for low P concentration and doesn't produce any sludge during or after the process (Loganathan et al., 2014).

A recent report published by fortune business insight predicted a compound annual growth rate (CAGR) of 6.28% for speciality fertilizers in the upcoming years (2019–26), which indicates the significant demand for water-soluble fertilizers (Fortune business insight, 2020). Hence, the recovery of water-soluble nutrients from urine is sustainable and expected to be economically viable in the upcoming times. From the available conventional adsorbents, the focus on choosing biochar for recovering the nutrients could be explained with rational justifications. Firstly, unlike other adsorbents such as zeolite, activated carbon, alumina, and silica gel, biochar is produced from the wastes. It adds value to the management of waste products and at the same time, makes it comparatively more economical. Secondly, the annual CAGR of biochar in the upcoming years is estimated to be at 16.45%, which is very encouraging for the biochar industries. It implies that the biochar industry is expected to grow by more than 15% each coming year (2020–2026). The global biochar market is expected to grow from 1385.94 million USD in 2019–3457.61 million USD in 2026 (Report linker, 2020). With the recent developments in the biochar production techniques, the production cost could range from 10 to 30 USD t<sup>-1</sup> which is much cheaper than charcoal (150–300 USD t<sup>-1</sup>) (Marousek et al., 2019a). These estimates and statistics support the biochar's economic potential as an adsorbent and encourage the use of biochar in different environmental fields.

This review article explores the nutrient recovery paradigms from source-separated human urine for closing the nutrient gap between wastewater treatment and agricultural productivity. Further, it emphasizes the nutritional value of human urine that has been lost as well causing additional pollutant load to WWTPs and the challenges associated with its direct use as fertilizers in

agricultural productivity. This review investigates the various merits and demerits of reported methods of nutrient recovery from human urine. Further, it emphasizes on nutrient recovery from human urine using biochar as a cost-effective adsorbent. The detailed mechanism of nutrient adsorption by biochar, various possible strategies of preparing engineered biochar aimed for recovering nutrients from human urine with the potential challenges and opportunities were deliberated in detail. Further, the application of nutrient-loaded biochar on the agricultural field has also been discussed to evaluate a recycled nutrient's effect on soil and crop yield. Moreover, the economic prospects of the nutrient recovery process using biochar have been discussed to stress the industrial application of this process.

## 2. Nutrients in urine

Urine is a liquid waste of animals separated from blood by the process of filtration called urination. Its composition is diverse as it contains compounds such as phosphorus, nitrogen, potassium, sodium, chloride, creatinine, and other dissolved ions along with 95% of water. Depending upon feeding habits, consumption of drinking water, physical activities, age, and other environmental circumstances average nutrient varies such as ammonium (0.32–0.5 g/l), phosphate (0.3–1.07 g/l), potassium (0.16–4 g/l) (Maurer et al., 2003). On average, an adult human produces 1.6–1.7 g of phosphorus every day, and around 60% of these phosphorus excreted out during urination. Based on the world's population (7.5 bn) 25 ton/year of N, 1.8 ton/year of P are excreted with urine each year. Recovery of those nutrients could have a market value of 20 bn USD/year (Larsen, 2020). The typical composition of adult human urine and its concentration are shown in Fig. 1 (Rose et al., 2015).

### 2.1. Traditional ways of using urine as a fertilizer and its associated problems

Urine is being used as a major source of nutrients for agricultural productivity in rural areas worldwide (Table 1). Apart from the

fertilizing potential of human urine, few researchers reported using human urine or along with plant extracts as pesticides and larvicides while growing herbal plants (Chawla, 2010). In many circumstances, direct use of human urine as fertilizer was envisaged with enhanced crop yield than the non-fertilized plants, in few cases, crop yield was almost the same as that of conventional NPK fertilizer (Pradhan et al., 2007). Still, the grown plants' hygienic quality was assured after tested free from microorganisms such as faecal coliforms, enterococci, clostridia, and coliphages. These studies concluded that urine, with or without the additional supplements, could be a critical substitute for the chemical fertilizer.

Repeated use of urine to the soil could increase the pH of 0.5 and electrical conductivity by 100  $\mu\text{S}/\text{cm}$  (Sene et al., 2019), which in turn affects the survival of helpful microbes like mycorrhiza fungi and reduces the plant root efficiency while absorbing nutrients through the diffusion process. It also has many adverse effects on the availability of micro- and macro-nutrients in the soil. Besides, urine has some common side effects such as itching, diarrhoea, pain, fatigue, and fever on the person or communities using it in agriculture. In the case of mishandling or improper storage, odour and flies may intensify the hazardous diseases in nearby areas. The application of human urine in the agricultural field has to confront some of the existing misconceptions and prejudices. Moreover, improper transportation and storage lead to excretion and evaporation that causes significant changes in the urine's mineral content (Nagy et al., 2019). Urine is considered microbe-free when collected from a healthy person. However, it is much more prone to contamination when exposed to the environment. While urine was contaminated, they may be harmful to the crop/vegetables and the persons cultivating and consuming the vegetables. Also, in terms of hygienic perspective, the storage and the use, need advanced precaution. World Health Organization (WHO) recommended that the storage of urine up to 6 months prior to use could reduce the pathogens and help achieve increased pH of 9 and augmented ammonium concentration (Mora-Ramírez et al., 2019).

Despite of numerous benefits such as urine's role in fertilizer, it's potential in reducing dependency on chemical fertilizers, and low economical cost; urine also has few negative impacts. Direct

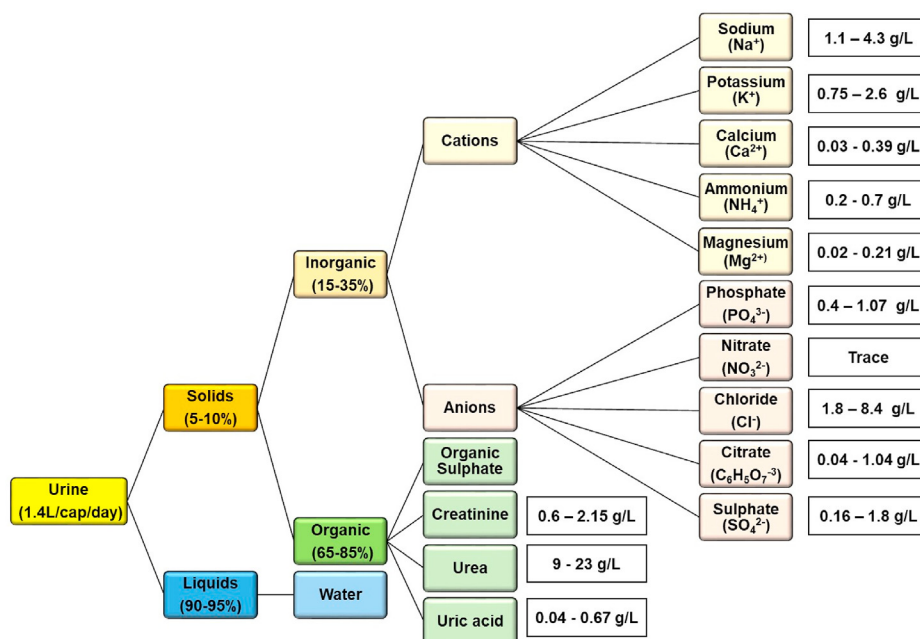


Fig. 1. Typical composition of adult human urine along with its concentration.

**Table 1**  
Global studies reported on edible crops cultivated by directly utilizing human urine as fertilizer.

Continent	Region	Crop	Type of study	References
<b>Africa</b>	Tanzania	Spinach		Chaggu et al. (2002)
	South Africa	Spinach	Pot	Kutu et al. (2011)
		Beetroot, Carrot, Maize, Tomato	Pot	Mnkeni et al. (2008)
		Cabbage, Spinach	Pot	Mnkeni et al. (2005)
	Nigeria	Kola	Field	Babatunde et al. (2015)
		Okra	Field	Akpan-Idiok et al. (2012)
		Amaranth	Field	AdeOluwa et al. (2012)
	Uganda	Maize	Plots	Andersson (2015)
	Zimbabwe	Wheat, Maize	Field	Guzha et al. (2005)
	Ghana	Cabbage	Field	Amoah et al. (2017)
		Sorghum	Field	Germer et al. (2011)
<b>Asia</b>	India	Bitter orange	Tray/Pot	Ganesapillai et al. (2016)
		Aquaculture	—	Rana et al. (2017)
		Banana, Maize	Field	Sridevi et al. (2009)
	Nepal	Cabbage, Cauliflower, Mustard, Potato, Radish	Field	Pradhan et al. (2011)
	China	Wheat, Corn		Esrey et al. (2001)
		Bamboo, Rice		Mang et al. (2007)
	Japan	Vegetables and fruits		Matusi et al. (1997)
	Vietnam	Rice, sweet potato, corn	Field	Jensen et al. (2008)
	Indonesia	Green amaranth	Seed bed	Kurnia and Azis (2016)
	Srilanka	Bean	Pot	Ranasinghe et al. (2016)
<b>Europe</b>	Finland	Tomato	Pot	Pradhan et al. (2009)
		Cucumber	Field	Heinonen-Tanski et al. (2007)
		Cabbage	Field	Pradhan et al. (2007)
		Pumpkin	Plots	Pradhan et al. (2010a)
		Red beet	Field	Pradhan et al. (2010b)
	Germany	Ryegrass		Winker et al. (2010)
	Sweden	Wheat	Pot	Ganrot et al. (2008)
		Leek	Field	Richert et al. (2010)
	Switzerland	Different vegetables		Maurer et al. (2003)
<b>North America</b>	Mexico	Lettuce	Plots	Guadarrama et al. (2002)
		Lettuce, Beet root	Pot	Mora-Ramírez et al. (2019)
	United States	Snap bean, Turnip	Plot	Pandorf et al. (2018)
<b>Australia</b>	French Polynesia	Papaya, Hibiscus, Serianthes	Pot	Beaune (2018)

application of urine could increase the possibility of pathogen contaminations and associated diseases (Karak et al., 2011); further, the high saline content of urine could increase the soil's salinity, impeding the plant growth (Sene et al., 2019). Moreover, the direct application of urine needs a pretreatment before their soil utilization, which adds an extra step to the process. However, the nutrients present in the urine opens up several opportunities such as its potential for wider adoption and implementation, local collection and processing units, development of local fertilizer markets, a potential substitute for synthetic fertilizers (lessening the dependency on finite resources), and also reduces the chances of eutrophication.

## 2.2. Importance of recovery of P and N from human urine

The environmental concerns such as eutrophication and more extensive dependence on finite P resources are the two driving causes for the recovery of P and N from wastewater and human urine. The nutrient present in the urine might spontaneously crystallize and precipitate as struvite that could block the sewage treatment plant valves, and further might result in damaging the sewage treatment pipelines (Wanstrom et al., 2019). The primary driver for P's recovery from the wastewater is preventing pollutants from entering the environment, causing the eutrophication (Law et al., 2019). In industrial countries, the costs for eliminating the nutrients are estimated at 20–40 USD/cap/year. Recovery of nutrients will save 150–300 bn USD/year (for 7.5 bn of the global population) (Larsen, 2020). Apart from the pollution control perspective, the recovery of these inorganic nutrients could be reused in agricultural sectors. Additionally, the recovered P and N

could be further purified and processed to use in many industrial sectors of detergents, fertilizers, cement, food additives, and others (Sartorius, 2012). When recovered from the human urine through minimal-cost investing methods, inorganic nutrients could be an excellent asset for poor farmers who could not afford the market minerals due to high cost (Cordell and White, 2015). Hence the advocacy of nutrient recovery from human waste ensures the quantity of food production without compromising quality. Thus, proper recovery and reuse of P and N from urine could empower the fulfilment of various goals like environmental protection, food security, energy generation, and sustainable sanitation process.

## 2.3. Various recovery processes of P and N from human urine

Many recovery processes of inorganic nutrients (P and N) from urine include physical separation, biological removal, and precipitation as struvite was reported. The efficient consideration of the process includes source, availability recoverability, and reusability of the nutrients. Furthermore, source separation of urine can facilitate different recovery techniques that could produce superior quality of nutrients. For instance, industrial or domestic wastewater or source-separated human urine require different recovery techniques and yields different quality of nutrients. Therefore, it is preferable to segregate at source for efficient nutrient recovery. These system limitations include the non-availability of large on-field land space, management, lack of infrastructure to facilitate source-separated collection of human urine, and exposure of the user to the unhygienic environment during handling of the wastewater/urine.

Besides, the large-scale recovery processes include the transfer



of the wastewater or human excreta to places farther from the locality outside the city by large pipes, which causes the reduction of contamination or spread of pathogen causing diseases (Bhandari et al., 2016). Almost more than 30 processes are available to recover or remove phosphorus from urine/excreta and wastewater (Harder et al., 2019). Other broad range of large-scale nutrient recovery plants includes wastewater-fed aquaculture, commercial level struvite recovery plants, and precipitated calcium phosphate from wastewater treatment plants. Although several methods exist for recovering nutrients from urine, this section briefly discusses the most efficient and commonly used methods. Fig. 2 depicts the overview of various technologies available to recover nutrients such as N and P from urine. The removal efficiency (numerical values) of different procedures as depicted in Fig. 2 is assigned from Table 2. Moreover, the merits and demerits of various nutrient recovery technologies and their efficiency are also briefly outlined in Table 2.

Biological methods rely on living systems for remediating environmental pollutants. Some standard processes such as accumulation by prokaryotes (Kashima et al., 2020), by algae (Bunushree et al., 2020), constructed wetlands (Luo et al., 2018) were reported. Further stabilization studies on source-separated human urine with nitrification could be denitrified autotrophically by anammox bacteria (Udert and Wachter, 2012). However, biological nitrification of human urine is highly challenging as it requires a synergistic interaction of ammonia and nitrite-oxidizing bacteria (Udert et al., 2003). Biological methods are highly effective and involve relatively less operational costs. Although biological methods do not involve the use of chemicals, they have their demerits. Biological methods such as wetland construction require a large area for the operation; living organisms' involvement makes the recovery process longer comparative to other available recovery methods.

Chemical methods are highly effective in recovering the nutrients from the urine; chemical processes consume relatively lesser time than other methods. Some prominent methods are Struvite precipitation (Wei et al., 2018), electrodialysis (Wang et al., 2017), and ion-exchange methods (O'Neal et al., 2013). However, these

processes involve a significantly large amount of chemicals that add the cost to the overall recovery and produce a large amount of sludge whose disposal is a prime concern. Some of the chemical methods become less specific when a particular ion is targeted.

The most widely used process-based upon physical phenomenon are air stripping (Wei et al., 2018), sorption (Beler-Baykal et al., 2020) and membrane-based filtration which includes reverse osmosis and ultra-filtration (Zhang et al., 2014). Although physical processes are efficient in removing pollutants, the membrane-based process is not selective towards ions. Process-based on membrane-based separation requires more capital investments, whereas air stripping is not applicable for the removal of phosphate. On the other hand, the sorption process is observed to overcome the above major concerns.

The sorption process does not involve extensive use of chemicals, which eliminates the problem related to sludge. The procedure involved in sorption is relatively fast and straightforward (Loganathan et al., 2014), making the process more convenient for the recovery of nutrients. Due to its high efficiency in recovering the nutrient and low capital investment sorption stands out to be a better option. The sorbent can be reused, and the nutrients can be separated after requisite treatment makes the sorption process more economical and sustainable. In the sorption process, choosing an efficient sorbent is more critical. Sorption with biochar is an economic and preferable option because the P and N removed using biochar need not undergo any other special treatment. Instead, it can be directly applied in the agricultural field. Thus, the recovery process of nutrients with biochar became more economical and could be directly applied into the agricultural land to act as slow realizing fertilizer, soil conditioner, and controls the excessive leaching warrants biochar as a potential candidate for biosorption.

### 3. Biochar

Biochar is a solid material produced by the carbonization of biomass (Mohan et al., 2014). Based on the operational conditions and feedstock type, a wide variety of biochar can be prepared through pyrolysis (Lehmann and Joseph, 2015). Biochar has a wide

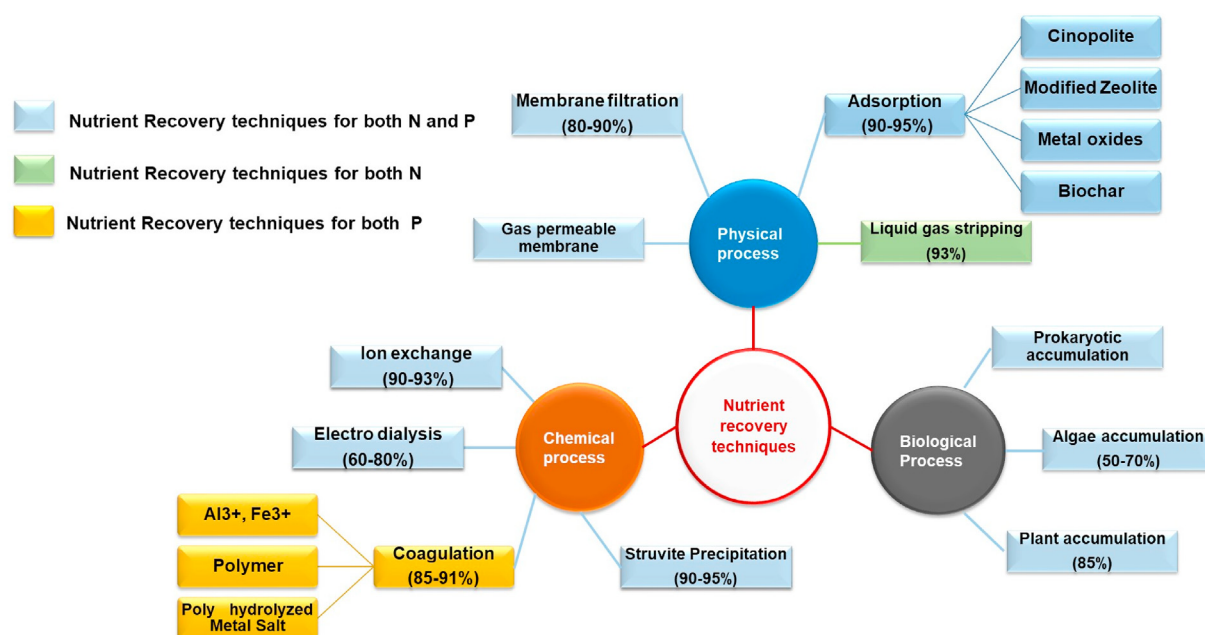


Fig. 2. Various technologies for the recovery of nitrogen and phosphorous based components from human urine.

**Table 2**  
Merits and demerits of nutrient recovery technologies from human urine.

Process	Source	Target molecule	Initial conc. (mg/L)	Efficiency (%)	Advantages	Limitations	References
Physical process Air stripping	Human urine	Ammonia	5615	93	✓ Highly successful in large scale treatment ✓ Eco-friendly and economical	× No phosphorus removal × Susceptible to pollution	Wei et al. (2018)
Membrane separation	Human urine	Ammonium, Phosphate		50–80 90>	✓ High efficiency ✓ Needs less space ✓ Simple operational techniques	× High energy and capital cost × High level of pre-treatment is required	Zhang et al., 2014
Freezing	Human urine	Ammonium	3000	90	✓ Works well with other recovery methods ✓ Relatively insensitive to change in concentration and type of feeds in wastewater	× Low efficiency in P removal × High energy requirement	Ganrot et al. (2007)
Distillation and nitrification	Human urine	Nitrate, Ammonium		95	✓ Efficient removal of nitrogen ✓ Works well with other recovery methods	× Substantial volatilization of nitrogen oxide × High energy consumption	Udert and Wachter (2012)
Chemical process Ion exchange	Human urine	Phosphate	14–61	90–93	✓ High efficiency ✓ Simple equipment, easy operation ✓ No or little use of organic solvents	× Non-selectivity of similar charge ions × Sometimes poor production of products × Large pH change	Hedstrom et al. (2006)
Chemical precipitation	Human urine	Phosphorus Nitrogen	312 7000	85 91	✓ High efficiency ✓ High degree of selectivity for removing substances	× High sludge formation × Sometimes slit formation with hazardous heavy metals	Kabdaşlı et al. (2018)
Struvite precipitation	Human urine	Phosphorus	384	94	✓ Good removal efficiency ✓ Low initial operation cost	× Less ammonia removal × Excessively high pH during reaction	Wei et al. (2018)
Urea hydrolysis	Human urine	Phosphate	45.3	82	✓ Fast precipitation ✓ Higher sludge reduction ✓ Lower DO consumption	× Fluctuation of efficiency at a different time interval × Multiple compound precipitate at a time	Chen et al. (2017)
Biological process Bioelectro chemical system	Human urine	Ammonia		60	✓ Reduced energy costs through the elimination of aeration	× High cost × Low efficiency	Ledezma et al. (2017)
Microalgal accumulation	Human urine	Ammonium Phosphate	79.9–83.7 11.7–13.3	52.6–55.6 20.4–67	✓ Production of a large amount of biomass ✓ Useful for the agricultural field and production of biofuel	× Require specific environmental and operational conditions × Difficulties in biomass harvesting and valorization	Santos et al. (2018); Behera et al. (2020)
Constructed wetlands	Human urine	Ammonium	141	85.4	✓ Simple and effective method ✓ Lower capital cost	× Requires larger space	Luo et al. (2018)

array of environmental benefits such as its ability of carbon sequestration (Rafiq et al., 2020), soil amelioration (Anwari et al., 2020), global warming mitigation (Demir et al., 2020) and remediation of contaminated soil (Ye et al., 2019a); photocatalytic activity (Ye et al., 2019b). Pyrolysis of agricultural biomass is an excellent substitution for open burning. It significantly reduces greenhouse gas emissions (GHGs); moreover, biochar fixes the carbon and slowly releases into the atmosphere. Hu et al. (2014) reported that biochar amendment in soil could reduce CO<sub>2</sub> and N<sub>2</sub>O emission and thus, biochar's application is an appropriate environmental management strategy for GHG mitigations. For instance, when biochar applied to soil at a rate of 49 ton ha<sup>-1</sup> for two years, it results in reduction of soil CO<sub>2</sub> and N<sub>2</sub>O by 33% and 55% respectively (Case et al., 2014). Biochar has a larger surface area due to its virtue of porous structure, which makes biochar a promising biosorbent. Hence, extensively used in the field of bioremediation such as in removing antibiotics (Kim et al., 2020), dyes (Chaukura et al., 2017), oils (E. Yang et al., 2018), pesticides (Sun et al., 2018), organic pollutants (Zheng et al., 2020) and heavy metals (Bai et al., 2020).

Although zeolite, aluminium oxide, ion-exchange resin,

activated carbon, loess, fly ash, and other synthetic materials are the few commonly used adsorbents, the carbonaceous materials are more effective in removing inorganic pollutants as compared to other adsorbents (Chen et al., 2007). However, the preparation of adsorbent zeolite, ion-exchange resin, and activated carbon are expensive due to their raw materials and processing cost (Kizito et al., 2015).

Biochar could be produced through a process in which biomass resources such as agricultural forest residue, food processing waste, solid waste, animal waste, and municipal sludge thermally decomposed in oxygen-less environmental conditions (Lee et al., 2019). The produced biochar has a large surface area, high carbon content, and multi-functional groups due to the thermochemical decomposition. Owing to its surface characteristics, chemical properties such as pH buffering capacity, ion-exchange ability, and other structural ability biochar are emerging as a cost-effective, environment-friendly, and efficient multifunctional adsorbent (Huang et al., 2020).

Due to its excellent stability, biochar could reduce the concentration of atmospheric CO<sub>2</sub> (Zhang et al., 2019). Furthermore, biochar has the efficacy in the adsorptive removal of organic and

inorganic contaminants, removing various heavy metals, and reducing heavy metals into their less toxic form (Zhang et al., 2019). Due to its large surface area and hydrophobicity properties, biochar provides a suitable environment for the growth of various microorganisms enhancing the soil microbial activity (Palansooriya et al., 2019).

### 3.1. Factors affecting biochar production

Biomass could be converted to biochar by adopting different thermochemical conversion techniques such as gasification, hydrothermal carbonization, torrefaction, and pyrolysis (Meyer et al., 2011). Although each technique has its pros and cons, pyrolysis has been reported as the extensively used thermochemical procedure for producing biochar from biomasses (Cao et al., 2014). Pyrolysis procedure involves the thermal treatment of biomass in an oxygen-free/limited environment (Biswas et al., 2017). Thermal techniques result in three products based on their states, i.e. biochar, bio-oil, and gases. The extent of biochar production can be influenced by the experimental condition and with the choice of biomass. In the majority of the cases, it was observed that experimental conditions such as moderate reactor temperature (300–450 °C), higher heating rate, low pressure, smaller biomass particle size favors the high yield of biochar with substantial carbon content, enhanced porosity and higher surface area (Rangabhashiyam and Balasubramanian, 2019).

Type of biomass, its pretreatment method, and operational condition during pyrolysis mainly affect biochar's physicochemical characteristics, which subsequently influence the biochar capacity to adsorb the targeted molecules (Cao et al., 2013). Due to its porosity and high surface area, biochar facilitates the necessary interaction between adsorbent and adsorbate by providing sufficient space for contaminants' adsorption (Rangabhashiyam et al., 2018). Depending upon the biomass type, its pretreatment and pyrolysis condition biochar generates multiple functional groups like carboxyl, hydroxyl, carbonyl, and phenolic hydroxyl, which helps ion-exchange reactions and adsorption between functional groups and the targeted molecules (Harvey et al., 2011). Some of the commonly used raw materials used to produce biochar for the adsorption of nutrients are rice and other agricultural wastes, animal manure, and sewage sludge (Dai et al., 2020). It is also reported that biochar produced at a temperature range of 500–600 °C is suitable for the adsorption of N (Alsewailah et al., 2019) and P (Park et al., 2015) (Table 3). A more detailed analysis related to biochar characteristics lies beyond the scope of this article.

### 3.2. Influencing factors of P and N adsorption in biochar

The adsorption of nutrient by biochar is occurring through several mechanisms such as ion exchange; electrostatic interaction; formation of hydrogen bond; exchange of ligand; precipitation on the surface; complex formation between the target molecule and functional group present on the biochar surface and/or either through physical adsorption (Huang et al., 2020). Adsorbate properties such as biochar's surface area, surface functional groups, modification with various metal oxides, and environmental parameters such as solution pH and simultaneous existence of other ions influence the mode and extent of nitrogen (nitrate and ammonium) and phosphorus (phosphate) adsorption. Different mechanisms of nutrient adsorption by biochar and its influencing factors are shown in Fig. 3.

The recovery of nutrients by using biochar is now emerging as a research focus, due to which a limited number of works have been reported to date. Hence, to understand the basic mechanism behind the adsorption process on biochar, different examples have

been cited from studies that involve human urine, synthetic urine, wastewater, greywater, and pure chemical aqueous solutions. Although the different aqueous solution has distinct chemical elements, which might affect the mechanism in a specific manner, the following instances could be taken into consideration for basic comprehension.

#### 3.2.1. Influence of surface area of biochar

Biochar produced at higher temperatures attributed to having high porosity. This pore serves as the active site for adsorption (Hu et al., 2020). Owing to its high porosity and massive surface area, biochar facilitates the adsorption of N/P by providing sufficient space. At high temperatures, various volatile compounds are released from the surface of biochar that leads to the formation of pores. However, at very high temperature, the pore structure collapse and blocked, which results in a reduction in the number of active sites (Yin et al., 2017). Numerous studies showed similar results in accordance with the surface area effect on adsorption capacity. Kizito et al. (2015) reported that Woody biochar has a larger surface area than rice husk biochar and observed to show 13% more adsorption of ammonium from pure ammonium solution. Zhang and Wang (2016) reported that a larger surface area enhances the adsorption of ammonium on the biochar surface. Bentonite hydrochar has a higher surface area due to its porous structure shown higher adsorption capacity than the later one. Ground corn biochar was observed to have higher phosphate adsorption capacity as their increment in pyrolysis temperature (Fang et al., 2014).

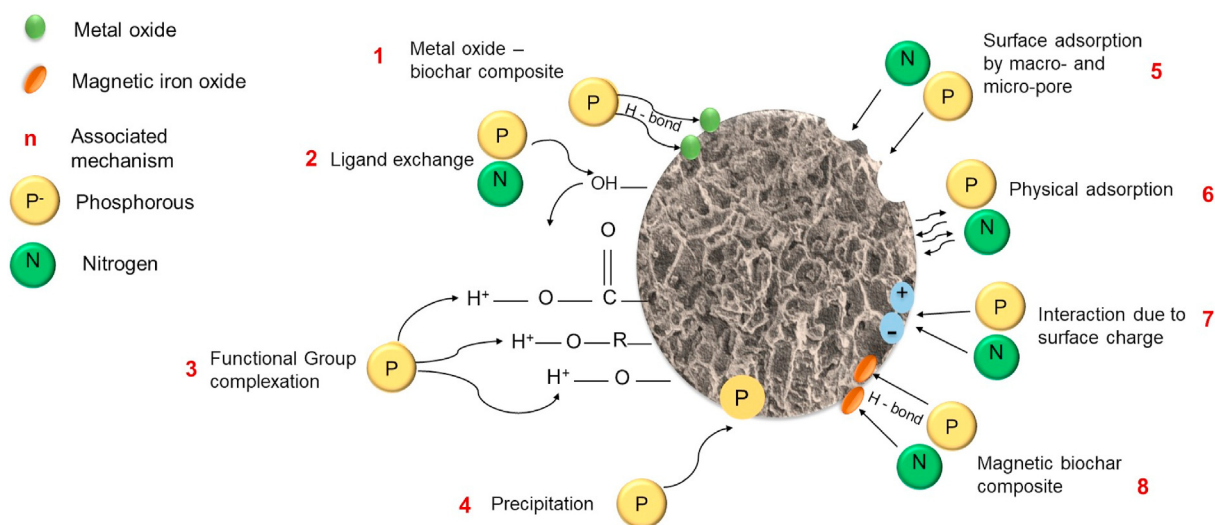
However, in cases of commercial wood biochar have a larger surface area (280 m<sup>2</sup>/g) shows less adsorption capability in removing ammonium when compared to press cake biochar which has a significantly lesser surface area (2.5 m<sup>2</sup>/g) (Takaya et al., 2016). It could be due to electrostatic interactions and ion exchange reaction between ammonium and biochar (Yin et al., 2017). Sumaraj and Padhye (2017) reported that when the pH of the solution is greater than that of the surface zero charges (pHpzc) of biochar, then biochar develops a net negative charge on its surface, and thus empowered the adsorption of ammonium ions. Similar results were observed when biochar is used to recover P from aqueous solutions. Zhou et al. (2019) found that with a decrease in zeta potential value, adsorption of P increases. In ion-exchange reactions, the ions were released from the adsorbent surface and then interacted with the target molecules (P and N ions) to form the precipitate. It have also concluded that adsorption of N and P depends on various other factors apart from the surface area of biochar (Zheng et al., 2018), where the role of biochar's surface functional group in carrying out the adsorption reactions have been highlighted.

#### 3.2.2. Influence of functional group present in biochar

Pyrolysis of biomass involves several reactions like aromatization, dehydrogenation, and dihydroxylation, resulting in the formation of many multifunctional groups such as carboxyl, carbonyl, and hydroxyl and phenolic hydroxyl on the surface of biochar (Li et al., 2013). These functional groups' presence plays a vital role in the adsorption of N/P by facilitating ion exchange between nitrate/phosphate/ammonium and functional groups (H. I. Yang et al., 2018). Wang (2015) observed a positive correlation between the removal efficiency of ammonium/nitrate/phosphate and the presence of acidic and basic functional groups present in the biochar. Acidic functional group and basic functional group present in the biochar are positively and negatively charged respectively due to the ionization of hydrogen and hydroxide ions (Hollister et al., 2013). Therefore positively charged ammonium exchanged with hydrogen and negatively charged phosphate, nitrate exchanged

**Table 3**  
Experimental conditions for the production of biochar and nutrient adsorption.

Sl. No.	Target nutrient	Biochar production condition	Adsorption condition	Adsorption capacity	References
1.	$\text{NO}_3^-$	Peanut shell biochar, Temp. 600 °C, $\text{MgCl}_2$ modified	Temp. $22 \pm 0.5$ °C, 60 rpm for 24 h	11.7%	Zhang et al. (2012)
2.	$\text{NO}_3^-$	Sugar beet tailings biochar, Temp. 600 °C, $\text{MgCl}_2$ modified	Temp. $22 \pm 0.5$ °C, 60 rpm for 24 h	3.6%	
3.	$\text{NO}_3^-$	Pinewood biochar, Temp. 600 °C, $\text{MgCl}_2$ modified	Temp. $22 \pm 0.5$ °C, 60 rpm for 24 h	0.6%	
4.	$\text{NO}_3^-$	Corn stover/oak wood biochar, Temp. 350/550 °C, Cold water extraction	Temp. $24 \pm 2$ °C, 400 rpm for 24 h	0	Hollister et al. (2013)
5.	$\text{NO}_3^-$	Oak sawdust biochar, Temp. 600 °C	Temp. $25 \pm 0.5$ °C, 120 rpm for 24 h	2.81 mg $\text{NO}_3^-/\text{g}$	Wang et al. (2015)
6.	$\text{NH}_4^+$	Oak sawdust biochar, Temp. 600 °C, $\text{LaCl}_3$ modified	Temp. $25 \pm 0.5$ °C, 120 rpm for 24 h	8.7 mg $\text{NH}_4^+/\text{g}$	
7.	N	Bamboo powder biochar, Temp. 900 °C	Temp. 10–15 °C, 120 h	1.25 mg N/g	Mizuta et al. (2004)
8.	$\text{PO}_4^{3-}$	Peanut shell biochar, Temp. 600 °C, $\text{MgCl}_2$ modified	Temp. $22 \pm 0.5$ °C, 60 rpm for 24 h	19.8%	Zhang et al. (2012)
9.	$\text{PO}_4^{3-}$	Sugar beet tailings biochar, Temp. 600 °C, $\text{MgCl}_2$ modified	Temp. $22 \pm 0.5$ °C, 60 rpm for 24 h	66.7%	
10.	$\text{PO}_4^{3-}$	Pinewood biochar, Temp. 600 °C, $\text{MgCl}_2$ modified	Temp. $22 \pm 0.5$ °C, 60 rpm for 24 h	0.1%	
11.	$\text{PO}_4^{3-}$	Corn stover/oak wood biochar, Temp. 350/550 °C, Cold water extraction	Temp. $24 \pm 2$ °C, 400 rpm for 24 h	2.15 $\mu\text{mol P/g}$	Hollister et al. (2013)
12.	$\text{PO}_4^{3-}$	Oak sawdust biochar, Temp. 500 °C	Temp. $25 \pm 0.5$ °C, 120 rpm for 24 h	10.2 mg P/g	Wang et al. (2015)
13.	$\text{PO}_4^{3-}$	Oak sawdust biochar, Temp. 500 °C, $\text{LaCl}_3$ modified	Temp. $25 \pm 0.5$ °C, 120 rpm for 24 h	19.75 mg P/g	
14.	$\text{PO}_4^{3-}$	Ground corn biochar, Temp. 300 °C	Temp. 30 °C, 200 rpm for 12 h	~7.5 mg P/g	Fang et al. (2014)
15.	$\text{PO}_4^{3-}$	Ground corn biochar, Temp. 300 °C, $\text{MgCl}_2$ modified	Temp. 30 °C, 200 rpm for 12 h	~8.1 mg P/g	
16.	$\text{PO}_4^{3-}$	Ground corn biochar, Temp. 450 °C	Temp. 30 °C, 200 rpm for 12 h	~7.6 mg P/g	
17.	$\text{PO}_4^{3-}$	Ground corn biochar, Temp. 450 °C, $\text{MgCl}_2$ modified	Temp. 30 °C, 200 rpm for 12 h	~8.2 mg P/g	
18.	$\text{PO}_4^{3-}$	Ground corn biochar, Temp. 600 °C	Temp. 30 °C, 200 rpm for 12 h	~7.7 mg P/g	
19.	$\text{PO}_4^{3-}$	Ground corn biochar, Temp. 600 °C, $\text{MgCl}_2$ modified	Temp. 30 °C, 200 rpm for 12 h	~8.2 mg P/g	



**Fig. 3.** Various adsorption mechanisms of nutrients (N, P) by pristine or engineered biochar.

with hydroxide due to electrostatic attraction. The presence of acidic and basic functional group enhance the uptake of ammonium and nitrate/phosphate by providing cation and anion exchange sites. The loss of  $\text{C}=\text{O}$ ,  $\text{C}=\text{C}$ , and aliphatic  $\text{C}-\text{O}-\text{C}$  groups in the case of biochar absorbed ammonium (Zeng et al., 2013). These

results indicate the interaction of functional groups with ammonium/nitrate/phosphate. As the biochar property varies with its operational condition and its feedstock type, biochar produced at higher temperatures is observed to have less functional groups in it. Biochar produced at low temperature has more negative acidic



groups and thus exhibits better adsorption capacity than those produced at a higher temperature (Zeng et al., 2013). Modification with Lanthanum (La) may lead to the induction of more acidic and basic groups on biochar surface, which is observed to increase the adsorption capacity towards ammonium and nitrate by 1.9 and 11.2 folds respectively (Wang et al., 2015). The adsorption of phosphate might be similar to that of nitrate for their negatively charged nature that may interact with functional groups in a similar fashion (Yin et al., 2017).

### 3.2.3. Influence of pH on adsorption capacity

pH value significantly affects the ion exchange capacity of biochar, thus influencing N/P adsorption (Q. Yang et al., 2018). Major ammonium was present in the ionic form in low or neutral pH so that it can be adsorbed on the surface of biochar due to ion exchange between cation and biochar. However, at alkaline pH, most ammonium is converted to a neutral ammonia molecule that cannot be adsorbed on the biochar surface (Huang et al., 2010). However, at very low pH, the ammonium ion adsorption decrease due to competition between  $\text{NH}_4^+$  and  $\text{H}^+$  ion for the limited adsorption sites of biochar (Mukherjee et al., 2011). pH also affects the phosphate adsorption by altering the biochar's surface charge. Biochar produced at lower temperatures (200–300 °C) has almost zero surface charge, resulting in no electrostatic interaction with phosphate ion, which lowers the phosphate adsorption capacity (Yin et al., 2017). It has been observed that the adsorption of nutrient from urine by the biochar occurred over a wide range of pH (6–12), however, the efficiency of the adsorption process vary depending on the pH, and the targeted ion. The adsorption of ammonium increased gradually from the pH 7 to 12; however, phosphate recovery efficiency significantly increased when the pH was varied from 6 to 9 and became stable in the range of 9–12 (Zheng et al., 2018). The recovery of ammonium achieved through electrostatic attraction, hence the change in surface charge occurred due to the variation of pH affect the adsorption process. When pH becomes more basic, then the biochar accumulate more negative charge on its surface, which consequently attract more positive ion. On the other hand majority of the phosphate recovery achieved through its precipitation as struvite (that occur at a specific range pH), but while dealing with urine it has been also observed that along with the struvite other minerals such as magnesium phosphate  $[\text{Mg}_3(\text{PO}_4)_2]$ , epsomite  $[\text{MgSO}_4 \cdot 7\text{H}_2\text{O}]$ , brucite  $[\text{Mg}(\text{OH})_2]$ , and montgomeryite  $[\text{Ca}_4\text{MgAl}_4(\text{PO}_4)(\text{OH})_4 \cdot 12\text{H}_2\text{O}]$  could also form. So to maximize the formation of pure struvite and minimize the formation of other undesired by-products, the pH range of 8.1–9.2 have been reported as the optimum pH for the phosphate recovery process (Udert et al., 2003). Both nitrate and phosphate bears a negative charge, which makes their adsorption less feasible at high pH due to competition between phosphate/nitrate ion and  $\text{OH}^-$  ion (Li et al., 2013). Thus, the pH of the solution plays an important role in recovering P and N from human urine.

### 3.2.4. Influence of coexisting ions

Urine is a complex mixture, apart from phosphate, nitrate, and ammonium there exist other ions such as sodium, chloride, sulfate, potassium, magnesium, calcium, and other trace amounts of enzyme (Rose et al., 2015). Some of these ions might interact with the targeted nutrients (P and N) to sorb on biochar influence the overall adsorption process. Gao (2015) reported that sodium chloride ions' influence does not significantly interfere with ammonium and the cotton stack biochar which may be due to the site-specific interaction of ammonium towards the biochar. The presence of chloride, nitrate, and sulfate does not significantly affect the ammonium adsorption capacity. According to Liu et al. (2020), the

presence of positively charged ion such as potassium, ammonium, and sodium in urine could have a synergistic effect on phosphate adsorption. The study observed that with the increment of ammonium and sodium concentration, the phosphate adsorption capacity of biochar increased by 14% in each case. However, phosphate, nitrate, chloride, and sulfate's mutual existence decreases the uptake of both phosphate and nitrate due to the competition between them for the ion exchange reactions (Table 4). Yao (2011) performed the adsorption with two different biochars and observed that chloride and nitrate do not affect the phosphate adsorption when adsorbed in digested sugar beet tailings. However, when adsorbed with tomato tissue biochar, phosphate adsorption capacity decreases in the presence of coexisting ions (Yao et al., 2013a,b). The two different outcomes could be due to the use of two different biochar produced at different operational conditions. Conversely, Kizito (2015) noticed an increment in adsorption capacity for ammonium from the piggery manure anaerobic slurry using wood and rice biochar. This result opens the possibility of enhancement in adsorption when other coexisting ions are present.

### 3.2.5. Influence of biochar size and dosage

Biochar size could play a crucial role in nutrient recovery. Increasing biochar size by granulation creates many channels, pores, and binder fibres, which help the adsorption process, make the magnetic biochar more preferable (Ren et al., 2015). Gong et al. (2019) found that micropores' adsorption capability is greater than that of mesopores when exposed to nutrients ( $\text{NH}_4^+\text{-N}$ ,  $\text{NO}_3^-\text{-N}$ ,  $\text{PO}_4^{3-}$ , and K). However, it is also crucial to note that high micropore structure not always ensure the increase in adsorption capacity, as pore size smaller than that of the targeted ions would not allow them to enter. Moreover, smaller pores could easily be blocked by the nutrients causing decreasing in adsorption capacity. So a micropore of size greater than 0.6 nm is preferable for the adsorption of nutrients. Hence, it might seem relevant to consider appropriate biochar size, as not always completely powdered biochar (which might have a larger surface area and high porosity) could ensure higher adsorption capacity.

Similarly, the dosage of biochar could also affect the adsorption capacity of biochar and recovery efficiency of nutrients. When biochar dosage was varied from 0.08% to 8% in hydrolyzed urine, the adsorption capacity of ammonium and phosphate decreased, however, the recovery efficiency increased. With the increment in dosage, phosphate's recovery efficiency surpasses 95%, whereas the ammonium recovery efficiency increased from 10% to 70% (Liu et al., 2020). Bai et al. (2018) also get a similar result when the biochar ammonium adsorption potential of biochar have been explored in human urine. These results could be due to the increasing availability of active sites for adsorption, which compete for the target nutrients, and consequently, the adsorption capacity of biochar slightly decreases. However, due to sufficient availability of active sites, the residual ammonium and phosphate concentration decreases. The overall mechanism for the recovery of nutrients using biochar has given in Fig. 3.

## 4. Engineered biochar for enhanced recovery of nutrients

Biochar due to its sorption property is currently a popular choice for recovering nutrients from wastewater, especially from urine. Generally, biochar's are observed to have an overall negative charge on their surface. Thus it has a fair chance of adsorbing positively charged ion present in urine such as ammonium. Biochar produced at lower temperatures have more negatively charged functional group, which further improves ammonium's adsorption potential. When human urine is stored for a longer duration (more than 48 h),

**Table 4**  
Effect of coexisting ions on phosphate and nitrate adsorption by biochar.

Sl. No.	Biochar production condition	Co-existing ion	Adsorbed nutrient	Efficiency decrease due to co-existing ion (%)	References
1	Sugar beet tailing, Temp. 600 °C, Pyrolysis time. 2hr	Cl <sup>-</sup>	Phosphate	4.3%	Yao et al. (2011)
2	Sugar beet tailing, Temp. 600 °C, Pyrolysis time. 2hr	NO <sub>3</sub> <sup>-</sup>	Phosphate	11.7%	Yao et al. (2011)
3	Sugar beet tailing, Temp. 600 °C, Pyrolysis time. 2hr	HCO <sub>3</sub> <sup>-</sup>	Phosphate	41.4%	Yao et al. (2011)
4	Palm tree waste, Temp. 600 °C, Pyrolysis time. 3hr, Fe modified	Cl <sup>-</sup>	Nitrate	8.50%	Ahmad et al. (2018)
5	Lignite granular activated carbon, Temp. 600 °C, Pyrolysis time. 1hr, ZnCl <sub>2</sub> Modified	CO <sub>3</sub> <sup>2-</sup>	Nitrate	40.9%	Khan et al. (2011)
6	Lignite granular activated carbon, Temp. 600 °C, Pyrolysis time. 1hr, ZnCl <sub>2</sub> Modified	PO <sub>4</sub> <sup>3-</sup>	Nitrate	20.3%	Khan et al. (2011)
7	Date palm waste, Temp. 700 °C, Pyrolysis time. 4hr, Mg–Al modified	SO <sub>4</sub> <sup>2-</sup>	Phosphate	~2%	Alagha et al. (2020)
8	Date palm waste, Temp. 700 °C, Pyrolysis time. 4hr, Mg–Al modified	CO <sub>3</sub> <sup>2-</sup>	Phosphate	~2%	Alagha et al. (2020)
9	Date palm waste, Temp. 700 °C, Pyrolysis time. 4hr, Mg–Al modified	SO <sub>4</sub> <sup>2-</sup>	Nitrate	27.5%	Alagha et al. (2020)

the urea, present in the urine, undergoes hydrolysis by urease enzyme to form ammonia and bicarbonate, which increase pH of the solution. The adsorption of various nutrients like phosphorus and nitrogen on biochar could be affected by the change in hydrolyzed urine's ionic strength. This is because the electrostatic interaction and Vanderwaal's forces also play an essential role in the adsorption process (Ray et al., 2018). Thus storing urine could help recover more amount of ammonium ions (as at higher pH the biochar surface would be negatively charged that could efficiently attract the positively charged ammonium ions).

However, due to the negative surface charge biochar was rarely observed to adsorb phosphate (Xu et al., 2018). Moreover, Xu et al. (2019) documented that biochar produced from a wood waste could release phosphate into the hydrolyzed urine. Generally, biochars have a phosphate content range which varies from 0.06 to 3.18%, and their negatively charged surface might leads to the release of phosphate from the biochar surface into urine. However, metal treated biochar could significantly improve the adsorption capacity for phosphate. In recent years, studies have focused on the fabrication of novel adsorbent by impregnating biochar in metal oxides, metal salts, or both. AlCl<sub>3</sub>, MgCl<sub>2</sub>, LaCl<sub>3</sub>, FeCl<sub>3</sub> are some of the extensively used metal salts used to modify biochar for adsorption of nutrients. Fe<sub>2</sub>O<sub>3</sub> and MgO are the most reported metal oxides used to improve the recovery efficiency of nutrients by biochar. Especially biochar treated with magnesium shows an incredible improvement in their adsorption capacity (Li et al., 2017). Biochar derived from different biomass tends to have distinct characteristics. However, the modification with different metal oxides observed to enhance the nutrient recovery potential of biochar from urine irrespective of biochar types (Zheng et al., 2020). Thus, surface modification of biochar with the metal oxides and their salts helps in the simultaneous recovery of P and N nutrients from urine.

Although traditional biochar is a promising adsorbent, several modifications were attempted to increase its adsorption efficiency and specificity. It can be physical modifications like steam activation or heat treatment, and chemical activation involves the treatment of biomass or biochar with acids and alkalis. Apart, biochar can be impregnated in a metallic solution either before or after the pyrolysis process. These modifications induce changes in physicochemical properties like porosity, surface area, surface charge, elementary composition and molar ratios such as H/C, O/C,

N/C (Ahmed et al., 2016). Engineered biochar has been observed to have high adsorption efficiency in case of the removal of different organic, inorganic pollutants and heavy metals. Nonetheless, biochar treated with metallic ions has reported in maximum cases for the removal of phosphate, nitrate, and ammonium. The different commonly used techniques implemented to modify biochar have shown in Fig. 4.

#### 4.1. Physical treatment

Physical treatment generally involves simple and economically feasible procedure. Biomasses are exposed to an oxidizing agent like carbon dioxide, air, and steam and not involve any chemicals during the modification procedure. However, these methods are less effective than activation performed by chemical treatment (Rajapaksha et al., 2016). Steam is allowed to pass through the produced biochar sample after the pyrolysis process. Steam activation removes the trapped partially combustion products formed during the pyrolysis process which increases the surface porosity. Further, it introduces functional group-containing oxygen and oxidizes its surface by generating hydrogen, carbon monoxide, and carbon dioxide. However, Lou et al. (2016) found out that there is no significant change in the biochar's P adsorption capacity with steam activation. Biochar is subjected to a higher temperature (700–800 °C) for 1–2 h. Heat treatment of biochar remove oxygen-containing groups like acids and ethers and introduce other functional groups such as Pyron type. This treatment enhances the surface area and hydrophobicity of biochar (Li et al., 2014). Although the subjection to a very high temperature increases the pore amount in the biochar, the loss of functional group and increase hydrophobicity makes the adsorption of P and N less conducive (Xie, 2015).

#### 4.2. Chemical treatment

Chemical treatment could be performed in a single step, or it could also involve a two-step modification procedure. In the single-step procedure, the biomass could be modified by the treatment with a chemical activating agent either prior or after pyrolysis. In the two-step activation process, the biomass was modified both before and after the pyrolysis process (Qian et al., 2015). Biochar can be treated with different acids before or after pyrolysis. Treatment

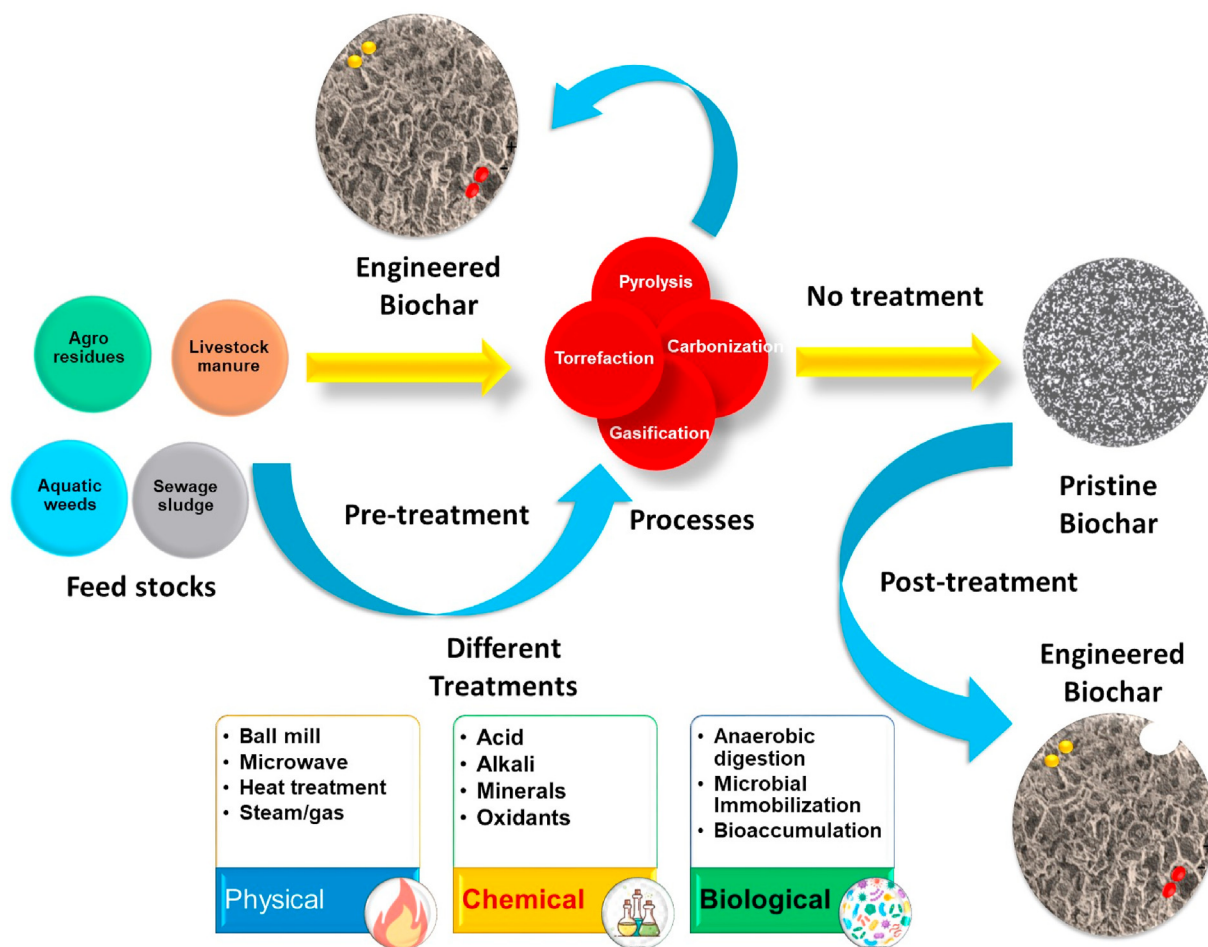


Fig. 4. Various treatment for the production of engineered biochar.

with acids modifies biochar surface by removing mineral elements present on the surface and increasing its hydrophilicity. Acid treated biochar have several acidic functional groups (i.e. carboxylic, ketonic, and hydroxyl) on its surface, which increase the polarity of the biochar surface. This increase in polarity the chemisorption capacity of biochar and efficiently remove pollutants from wastewater (Biswas et al., 2020). However, according to the findings of Park et al. (2015), biochar modified with an acid such as HCl, H<sub>2</sub>SO<sub>4</sub>, and H<sub>3</sub>PO<sub>4</sub> poorly adsorb the P from the aqueous solution.

Biochar allowed to soak in various alkali solutions up to 100 °C. Alkali modification produces a positive charge on the biochar surface and helps to remove negatively charged groups. Biochar treated with alkali observed to have a high surface area and exhibits surface aromaticity. This helps the biochar in the removal of negatively charged species and organic pollutants from wastewater (Liew et al., 2019). Takaya et al. (2016b) found that biochar activation with KOH has slightly increased the P adsorption capacity.

#### 4.3. Biological methods

Biological methods rely on living systems for remediating environmental pollutants. Prokaryotes, algae, and other microbes have been used to remediate several water pollutants. Thus, by immobilizing microbes on biochar surface, it could be used to remediate pollutants from wastewater. When *Rhodococcus opacus* was immobilized onto biochar loaded polyurethane, the

synthesized adsorbent could remove the aromatic hydrocarbons present in wastewater released from biomass gasification with a removal efficiency of 95% (Goswami et al., 2020). However, biological nitrification of human urine is highly challenging as it requires a synergistic interaction of ammonia and nitrite-oxidizing bacteria (Udert et al., 2003). The biological treatment of biochar is a relatively new concept; very lesser works have been reported in this context. The use of biologically modified biochar in the nutrient recovery from urine is not yet reported.

#### 4.4. Modification of biochar with metals/oxides for efficient adsorption

It has been noticed that biochar without any modification shows poor results in adsorbing phosphorous and nitrogen. It might be due to the poor electrostatic interactions between the negatively charged surface of biochar and negative phosphate/nitrate and the absence of requisite functional groups that help in ion-exchange reaction with targeted molecules. This issue could be overcome by treating biochar with metal oxides. When treated with metal oxides, biochar observed to have a significant change in surface charge, surface morphology, and functional groups. This increases the adsorption capacity of biochar dramatically (Wang et al., 2015). Numerous studies have verified the enhancement of adsorption capacity of biochar towards phosphate/nitrate when treated with metal oxide like MgO (Zhang et al., 2012), Fe<sub>2</sub>O<sub>3</sub> (Chandra et al., 2020), CaO (Liu et al., 2016), AlOOH (Jung et al., 2015b), La<sub>2</sub>O<sub>3</sub>



(Wang et al., 2015), and Heavy metals (Mosa et al., 2018) as compared to non-modified biochar. The increment in phosphate capability can be explained by phosphate's ability to precipitate on the surface by reacting chemically with metal oxides or it can be deposited on the surface by forming weak hydrogen bonding with metallic oxides.

Phosphate in the presence of Mg and ammonium precipitated to form an important compound called struvite  $[Mg(K,NH_4)(PO_4) \cdot 6H_2O]$ . Struvite recycling from wastewater treatment is considered an alternate option for chemical phosphorus fertilizer (Ganrot et al., 2007). Yao et al. (2011) observed that biochar and struvite could attach each other, which indicates that biochar not only adsorbs the phosphorous ion but also provide a platform to precipitate as struvite. When biochar enriched with phosphate applied to a field, it increases the soil fertility. The study of Liu et al. (2020) on the recovery of nutrient from human urine using biochar highlights precipitation and adsorption as two crucial nutrient recovery mechanisms. Thus, biochar loaded with struvite could act as a slow-releasing fertilizer. Takaya (2016) pointed out the positive correlation between Ca and Mg content in biochar and its phosphate adsorption capacity. Biochar produced from engineered tomato tissue and sugar beet tailing having Mg content of 8% and 10% respectively observed to have phosphate removing capacity of 88.5% and 73% respectively (Yao et al., 2013a). Similarly, Jung (2015a) reported that peanut shell biochar which is having more Mg content as compared to other biochar such as soybean stover, oak wood, maize residue, and bamboo wood shows the best removal efficiency of 61.3%. The enhancement in phosphate adsorption capacity of biochar could be due to the dispersed nano-sized MgO present on the surface (Yao et al., 2011). The surface of MgO treated biochar is generally positive in urine, which can form mono-, bi- and tri-nuclear complexes due to electrostatic interactions (Yao et al., 2011a). Magnesium ion can chemically react with phosphate molecules to form precipitate as  $Mg_3(PO_4)_2$  and  $MgHPO_4$ . Treatment with Mg has been observed to increase the active sites on biochar for phosphate adsorption.  $La_2O_3$  (Lanthanum oxide) also has a similar equal point of zero charges as that of MgO; thus, treatment with  $La_2O_3$  can also enhance the phosphate adsorption capacity (Park et al., 2015).

Most of the biochar modification was performed by soaking the biomass in requisite metal oxide (Mg, Fe, Al) or their salt for 2–12 h before pyrolysis (pretreatment). In a few cases, biomass needs to treat with metal solution after the pyrolysis process (post-treatment). However, this process of impregnation of biomass or biochar is a little complex and time-consuming process. To overcome these issues, the combined electrochemical modification (CEM) process was introduced and examined. Jung (2015b) produced Al modified biochar by performing the biomass solution's electrolysis with NaCl and Al as electrolyte and electrode, respectively. During the process, a current density of  $0.009396 \text{ mA m}^{-2}$  was maintained for 5 min, and then biomass was pyrolyzed at  $450^\circ\text{C}$ . Al modified biochar was reported to have an enhanced surface area with the presence of nano-sized crystalline boehmite ( $AlOOH$ ) on its surface. Jung and Ahn (2016) produced the Mg modified biochar as per the above method keeping  $MgCl_2$  as electrolyte and graphite as an electrode. Similarly, Jung (2015c) produced Mg–Al biochar composite by keeping magnesium chloride as an electrolyte and Al electrode. This modified biochar has been observed to have five times more adsorption capacity as compared to non-modified biochar. Thus, using innovative CEM techniques, metal-functionalized biochar can be produced with very little expense of time.

Studies have shown that phosphate is being precipitated on the surface of biochar in the forms of  $Mg_3(PO_4)_2$ ,  $MgHPO_4$ , or  $Mg(H_2PO_4)_2$  (Yao et al., 2013a,b). Still, the adsorption phenomenon is considered the dominant mechanism for the recovery of

phosphate (Yao et al., 2013a,b). Due to the positive surface charge of Mg-modified biochar, it seems theoretically difficult to adsorb positively charged ammonium. However, earlier studies pointed out the spontaneous precipitation of phosphate and ammonium in the form of struvite when Mg modified biochar is added to the urine (Udert et al., 2003).

In the majority of cases, the removal of finely powdered biochar from the urine solution could be another serious concern. However, if biochar can be modified with iron and its oxides then by using magnetic separation technique biochar can be easily separated. Fe modified biochar has a strong affinity towards phosphate, which may be due to the electrostatic interaction between negatively charged phosphates and positively charged modified biochar (Zhang et al., 2007). Biochar modified with Mg surmises a similar adsorption mechanism for nitrate even though  $Mg^{2+}$  and nitrate have not been observed to form precipitates. Further studies are needed to explore the primary mechanism that can explain nitrate and magnesium's interaction more appropriately. The sorption capacity and efficiency of pristine and engineered biochar for P and N recovery are given in Table 5.

## 5. Application of nutrient-loaded biochar on soil

Biochar application in the agricultural field reported enhancing crop yield. For example, when urine impregnated biochar applied in low doses to the pumpkin field, it increased the pumpkin yield by four folds (Schmidt et al., 2015). The application of biochar has also been observed to improve the soil's microbial dynamics (Wu et al., 2016). Therefore, biochar loaded with phosphorous and nitrogen from urine can be directly applied to the agricultural field. Due to the presence of an aromatic group, Biochar acts as a slow-releasing fertilizer and thus avoids excessive P and N leaching into the soil.

The majority of the agricultural fields are facing a deficiency of nutrients (P and N) for a long time (Li et al., 2007). Crops poorly take the total applied P (only 5–20%) (Price, 2006) and 70–80% of P retained in the soil get lost to water bodies due to rain. Lwin et al. (2017) discussed the adverse effect of phosphorous flow from agricultural land to wastewater. Nutrient loaded biochar can act as slow-releasing fertilizer and retain the P and N in the soil for a more extended period. Apart from the phosphorous adsorbed, biochar itself have a certain proportion of phosphorous in it, which can be directly available to crops (Chintala et al., 2014). The type of biomass and pyrolysis condition plays a vital role in determining the available P in the biochar (Kloss et al., 2012). Further, their study confirmed that woody biochar produced at moderate temperature ( $400\text{--}500^\circ\text{C}$ ) has increasing available P with an increase in temperature.

The application of engineered biochar after the adsorption of nutrients was observed to improve soil productivity, reduces phosphate loss, and sequester carbon in the applied soil (Yao et al., 2013a,b). When the biochar (that has been utilized to recover ammonium from urine) applied to the soil, the cation exchange capacity and the soil's pH improved, this study highlights the soil conditioner potential of biochar (Bai et al., 2018). Wang et al. (2017) reported that Mg–Al and Mg–Fe modified bamboo biochar adsorbed P from aqueous solution retains a high amount of P in the applied soil and enhance the lettuce seedling growth compared to that of control. Lettuce leaves grown in nutrient-loaded biochar were greener and healthier. Chen et al. (2017) investigated the effect of P-laden Mg modified biochar on soil lettuce system and finds that P-laden Mg modified biochar improves the soil pH, organic carbon content, soil moisture and available P in the soil by almost tenfold. P-laden biochar amendment significantly increases the plant height, fresh and dry weight. In a study, Mg modified biochar was utilized to recover the phosphorous from human urine when



**Table 5**

Adsorption capacity and efficiency of pristine/engineered biochar for nutrient recovery from human urine.

Sl. No.	Biochar type	Modifications	Nature of human urine	Targeted nutrients	Adsorption capacity (mg/g)	Adsorption efficiency (%)	References
1	Corn cob		Synthetic	Phosphate		14	Jena et al. (2020)
2	Corn cob	MgCl <sub>2</sub>	Synthetic	Phosphate		96	Jena et al. (2020)
3	Garden waste	MgCl <sub>2</sub>	Real	Phosphate	162	90	Liu et al. (2020)
4	Wood waste		Real	Phosphate	—	−4.5 ± 4.6	Xu et al. (2019)
5	Weathered charcoal		Synthetic	Phosphate	0.29–0.43	10 to 15	Zheng et al. (2018)
6	Wood waste	MgCl <sub>2</sub>	Real	Phosphate	118	97.2 ± 0.1	Xu et al. (2019)
7	Wood waste	AlCl <sub>3</sub>	Real	Phosphate	17.66	14.6 ± 1.4	Xu et al. (2019)
8	Wood waste	CaCl <sub>2</sub>	Real	Phosphate	7.62	6.3 ± 1.4	Xu et al. (2019)
9	Wood waste	FeCl <sub>3</sub>	Real	Phosphate	3.63–25.41	12.7 ± 9.5	Xu et al. (2019)
10	Populus xcanadensis moench	MgCl <sub>2</sub>	Real	Phosphate	116	57.6 ± 0.13	Xu et al. (2018)
11	Woody chips	MgO	Synthetic	Phosphate	2.52	86 ± 1	Zheng et al. (2018)
12	Woody biomass	MgO	Synthetic	Phosphate	2.75–2.84	95–98	Zheng et al. (2018)
13	Weathered charcoal	MgO	Synthetic	Phosphate	2.75–2.84	95–98	Zheng et al. (2018)
14	Saw dust		Synthetic	Phosphate	7782	—	Idrus et al. (2018)
15	Saw dust	MgCl <sub>2</sub>	Synthetic	Phosphate	32755	21.2	Idrus et al. (2018)
16	Populus xcanadensis moench	MgCl <sub>2</sub>	Real	Ammonium	47.5	35.5 ± 3.6	Xu et al. (2018)
17	Wood waste	MgCl <sub>2</sub>	Real	Ammonium	108	—	Xu et al. (2019)
18	Weathered charcoal	MgO	Synthetic	Ammonium	54.6–63.7	30–35	Zheng et al. (2018)
19	Woody biomass	MgO	Synthetic	Ammonium	45.5–54.6	25–30	Zheng et al. (2018)
20	Woody chips	MgO	Synthetic	Ammonium	52.9	28–30	Zheng et al. (2018)
21	Fecal sludge		Real	Ammonium	21.45	87.5	Bai et al. (2018)
22	Weathered charcoal		Synthetic	Ammonium	54.6–63.7	10 to 15	Zheng et al. (2018)

that nutrient-loaded biochar was applied to soil it was observed that more than ten folds increased the Mellich3 phosphate (plant extractable phosphate) concentration. This results in 27% and 46% longer root and shoots growth in mung bean plants (Jena et al., 2020).

Wen et al. (2017) with their polymer matrix biochar composite had adsorbed ammonium from aqueous solution and applied to the cotton plant. With N-laden biochar's application, the N leaching was observed to reduce, nitrogen use efficiency was increased and have a positive effect on cotton plants as slow-releasing fertilizer. Xu et al. (2018) found that Mg modified biochar didn't show any positive effect on maize and ryegrass. In contrast, Mg biochar after adsorbing nutrients from urine observed to enhance the plant height of maize and ryegrass. Researchers concluded that nutrient-loaded biochar can be used as a slow-releasing fertilizer for plant growth (Zhang et al., 2013). The slow phosphate releasing ability of biochar makes it an attractive option for recovering the nutrients and making them available in a form that the plants could easily intake. It is crucial to note that not all procedure implemented for the recovery of nutrients could make them bioavailable. For instance, the phosphate becomes unavailable to plants when separated from the water using ferrous sludge (Maroušek et al., 2019b). However, most studies were done at a lab-scale as pot experiments, and very few studies were conducted on the field scale.

## 6. Economic potential of the overall process

Innovation and competitiveness are the pivotal factors that ensure the commercial success of a product. Urbancova (2013) highlighted some of the essential characteristics of a product having a competitive advantage. To make the recovery of nutrient using biochar as an economically viable process, it needs to have the ability to substitute the currently used techniques for nutrient recovery, and the nutrient-loaded biochar should replace or minimize the heavy use of fertilizers. As the adsorption process is quite straightforward, so replacing the other energy-intensive and complex nutrient recovery process is possible. Further, innovation in the overall process would shorten production time, which would speed up the development of new products compared to their competitors. This includes, collection, transportation, storage, and

time required in the adsorption process, with technical innovation, more optimized procedures should be introduced to reduce the time consumption of the overall process.

To understand the industrial implication of the overall process, Maroušek et al. (2020) have presented a cost analysis of the phosphate recovery using biochar. The biochar has been modified with ferric chloride and calcium chloride, and their cost breakdown has been compared with conventional struvite production at industrial scale. Based on the study, it was found out that any biochar modified with 2.4 kg of 10% ferric chloride could potentially sorb around 2.5 kg of P per 100 kg of sorbent from wastewater of having an initial concentration of 80 mg P l<sup>-1</sup>. Considering these facts the total cost per application of 1 kg CaP ha<sup>-1</sup> comes out to be 163 USD, whereas the cost is around 10600 USD. So it is evident that with the implementation of nutrient recovery using biochar, the cost could be reduced significantly. The study also argues that with the modification of biochar by Calcium chloride, the cost of application could be reduced to 76 USD.

It has been reported that with the implementation of appropriate government policy, the biochar production cost could be reduced to a negligible amount. Vochozka et al. (2016) stated that the revenue obtained from the gate fee (fees for accepting bio-waste) is around 11.64 USD. This could compensate for the depreciation and running cost of 7.35 USD and 6.13 USD respectively. All the analysis is related to 1 ton of biochar. The pyrolysis process and production of biochar is more of a holistic process than producing biochar; it also produces bio-oil and gases of economic importance, which helps generate an additional amount of revenue from the whole process. A techno-economical assessment has been done in a similar note by Maroušek et al. (2019b). The use of biochar as a filter to recover nutrients from the anaerobic fermentation residues have been analyzed. All these results and studies show the economic viability of biochar and indicate the untapped potential of nutrient recovery from urine using biochar process.

## 7. Challenges and the road ahead in the nutrient recovery from urine

The nutrient recovery from urine using biochar is a clean and sustainable approach for resolving the water-food nexus's challenges. However, there are specific difficulties which are impeding

its application on a large commercial scale. The primary challenges, such as collecting the urine at a larger scale, transportation, storage, preparation of appropriate biochar for the process, and fabrication of suitable reactors for the adsorption process, need to be addressed. These, along with certain secondary situation-specific challenges need to be overcome to implement the nutrient recovery by biochar and its subsequent use in the agricultural field. Thus, this research domains promise an ample amount of research to subdue the challenges.

### 7.1. Challenges in the nutrient recovery from urine

The composition of urine is affected by many factors such as geographical region, sexuality, and diet of the person; thus, collecting and storing the urine sample in a single place for large-scale operation increases the variability of the urine sample. Although urine came out of healthy organisms generally are reported to have no or significantly fewer bacteria. However, it is essential to note that urine could have several microorganisms, such as virus, bacteria, parasitic protozoans, and blood flukes. Moreover, urine has a very high amount of biodegradable organic compound (Giannakis et al., 2018), due to which the urine generally contaminated with a variety of microorganisms like bacteria and pathogens further leads to several infections upon improper handling. Schistosomiasis is one of the most common infections in developing countries (mainly in the African region) caused by *Schistosoma haematobium* (urinary blood fluke). The eggs are excreted with the urine, these eggs require aquatic environment for their hatching, and the larvae infect certain species of snails present in freshwaters. Moreover, after certain developmental stages, the larvae develops the potential to infect humans. However, if the eggs were stopped from reaching snails, then the transmission cycle could be broken, as the eggs could not survive more than a few days (Stenström, 2004). Thus, the urine should be stored for a more extended period (1–6 months) to diminish pathogens' effect. Nevertheless, suppose the urine is collected in a significantly smaller scale (individual house) and intended to use for personal gardening. In that case, it could be used without storage or with a little span of storage as the chances of contamination becomes higher when it is collected on a larger scale.

The presence of bacteria produces spontaneous changes in urine; the essential processes are ammonia volatilization, microbial urea hydrolysis, and mineral precipitation (Arias et al., 2019). These metabolic processes will bring several changes to the urine's chemical composition, pH, colour, turbidity, and odour. Hydrolysis of urea converts it into ammonium and thus raises the solution pH. It has been observed that alkaline condition (pH around 9) could inhibit several microbes. While storing the dilution of urine needs to be avoided, as in concentrated urine, it becomes difficult for thriving microorganisms (Höglund et al., 2002). Hence urine could be kept at low temperature (4 °C) in a sterile place to stop the microbial metabolism by seizing their growth.

Urine is prone to cross-contaminate with faeces and results in the transmission of pathogens from faeces to urine, which polluted the urine intended for reuse in agriculture (Höglund et al., 2002). Cross-contamination with faeces is a significant issue from health hazards' perspectives and makes the overall process as cost-intensive. Thus a paradigm shift on retrofitting conventional toilets with urine-diverting dry toilets is the high need of the hour so that the faeces will be separated directly in the toilet and makes the process more simple and sustainable. Apart from the biological contaminations, urine could also be contaminated from harmful chemical compounds. In recent years, the use of pharmaceuticals products has been increased tremendously. These compounds could undergoes certain drug metabolism pathways and results in

the formation of endocrine disrupting chemicals and compounds (EDCs). The exposure to EDCs could contribute to several acute and chronic diseases such as cancer, diabetics, infertility, and brain damage (Salehi et al., 2018). Therefore, the mixing of contaminated urine with the normal urine might create a problem during the treatment.

Biochar's surface generally charged negatively makes the adsorption of P and N difficult. So appropriate surface modification with metal oxides has to be done to develop the desired characteristics of biochar. It is also reported that the adsorption of nutrients with biochar is more efficient at low concentrations. In urine, the ammonium and phosphate concentration were observed to be 8203 mg  $\text{NH}_4^+$ /L and 318.5 mg  $\text{PO}_4^{3-}$ /L, respectively (Xu et al., 2018). To reduce the concentration of nutrients, it can be diluted with water or the urine can be striped with air for ammonium reduction. Freezing the urine and removing the supernatant will reduce the nutrient content of urine (Ganrot et al., 2007). The above-suggested methods can be implemented to lower the nutrient concentration, which may results in higher efficiency in adsorbing the nutrient using biochar. Biochar produced at a temperature range of 400–500 °C generally has a highly ordered aromatic carbon structure which helps in the adsorption of heavy metals. Biochar produced at a pyrolytic temperature of 300–400 °C is reported to contain a maximum amount of polycyclic aromatic hydrocarbon (PAHs) (Lyu et al., 2016). In general, biochar produced at a lower temperature (<400 °C) from a feedstock containing compounds such as polyvinyl chloride, pentachlorophenol could produce potentially toxic compounds (polychlorinated biphenyl-*p*-dioxins and furans) during pyrolysis, which might be released into the environment when applied (Fredde et al., 2012).

After the adsorption process, the adsorbent needs to be removed from the source-separated urine. Using normal biochar may create problems in the removal steps. However, the use of a specific modification of biochar (with Iron) helps to overcome this difficulty of separation after treatment. The efficiency of biochar can be increased by granulating it; larger sizes of adsorbent reduce lots of effort in the separation process. Many studies criticize the adsorption process as the transfer of pollutants from one place to another. However, the recovery of nutrients from urine using biochar is not a mere transfer of phosphorus and nitrogen from urine to another place, instead it benefits the agricultural field through a nexus approach. The biochar after the adsorption process has nutrients loaded in it; this can be directly applied in the agricultural field as slow realizing fertilizer. The nutrients combined with the desired biochar properties could be used as a potential alternative against the chemically used fertilizer. The overview of various facing challenges during the recovery of nutrients from human urine is summarized in Fig. 5.

**Technical challenges:** The nutrient recovery from urine is quite efficient in laboratory scale, however, the instance it has been scaled up (while implementing the recovery techniques in a pilot-scale) the efficiency of the process drops significantly. So, to make the process viable in a real-time scenario (i.e. in village or city), more innovative and efficient technologies need to be developed to carry out the operation on a much larger scale. One of the significant technological challenges in the overall process is to collect and store urine. The majority of the households do not have any facility to source separate the urine. Moreover, the infrastructure is very limited in the poor and developing countries. Hence, it becomes essential to upgrade the sanitization system to collect and separate the urine from the households, educational institutions, business hubs, and other organizations.

**Social challenges:** Urine considered as a waste material released from animals, the majority of the general population are not aware of the scientific value and fertilizing potential of urine.



Fig. 5. Numerous challenges associated with the recovery of nutrients from urine.

This social stigma attached to human urine impedes its application. Urine's origin and its strange odour create a negative impression on people's perception, making it more difficult to get utilized by the common public. People are not ready to accept the products derived from urine. The general mass have a perception that the product derived from a waste might have some harmful components; thus, they are not yet convinced with the product safety.

**Economical challenges:** To make anything viable at the industrial scale, it becomes crucial to acknowledge the techno-economic challenges and overcome them. The nutrient recovery from urine using biochar is still an emerging field. Several studies have been carried out to understand the process at a technical level, however, the overall process's economic assessments have yet to be done properly. This would provide us with a better idea to make this process more industrial oriented. One of the significant economic challenges would be to commercialize the product. As the initial cost of investment would be higher, so to make the product sustainable at markets, the cost should be competitive. Moreover, as the product is associated with urine, the social stigma towards the product needs to be eliminated, so that it would get the desired market value. It is noteworthy to mention the popularity biochar enjoys in the farming community, so nutrient recovery using biochar would be an excellent opportunity to commercialize urine fertilizer potential.

**Political/Institutional challenges:** Even after overcoming all the bottlenecks associated with technical, social, economic challenges, the chances of successful implementation is not ensured. This requires the support of government, institutions and all the stakeholders. Lack of motivation in implementing nutrient recovery from urine using biochar could impede the application at a large scale. The threat possessed by the depleting nonrenewable phosphorous and nitrogen source needs to be realized by the government authorities, and robust legislation needs to shift the focus from non-renewable source to a more clean and renewable source of nutrients. Finally, proper coordination between different stakeholders needs to be established. This is because the overall nutrient recovery process integrates several processes such as urine collection, transportation and storage, biochar production, carrying

out the nutrient recovery reactions, and applying the nutrient-loaded biochar in the agricultural field. Therefore, a problem in any of these stages would hamper the overall process.

## 7.2. Future perspectives

In recent decades, biochar research has rapidly emerged in the production aspects. Still, much research has to be conducted on application aspects in the real-time scenario. The trends of biochar research for recovering inorganic nutrients should address the following limitations to be overcome in future research are as follows:

- Effects of agroresidual feedstocks and pyrolysis conditions to produce biochar for subsequent utilization to recover nutrients from human urine and its impact on farming activities while applying on the soil has to be outlined
- Synthesis of biochar based functional materials for the specific recovery of N and P from human urine has to be studied
- Agronomical and environmental benefits of biochar while utilizing for recovery of N and P from human urine has to be elucidated
- Ecotoxicity of nutrient recovered biochar applications in the agricultural field has to be assessed long term as the testing of persisting free radicals in biochar in its still emerging stage
- Research on modified biochar and its applications is still in its preliminary stage

The challenges in the lab and industrial-scale include large scale collection and storage of human urine for further use in resource recovery perspectives. Also, urine is more prone to microbial contamination, affecting the physical and chemical properties, thus making the whole process complicated. Sometimes, few difficulties have been witnessed by this process of resource recovery by pristine/engineered biochar. The nutrients-adsorbed-biochar could be used in the agricultural field as a slow-releasing fertilizer. Future works should concentrate on the development of simpler, economical collection and storage techniques of human urine on a



mass scale, which demands the innovation in retrofitting the conventional sanitation facilities. Biochar produced at a lower temperature could contain toxic compounds that may harm soil and plants, so biochar preparation needs special attention for the desired outcome. The application of nutrient-enriched biochar as slow fertilizer needed further investigation on a larger scale for effective implementation at grass-root levels.

## 8. Concluding remarks

In the world of growing population, the scarcity of inorganic nutrients like phosphates and nitrates can be fulfilled by recovering them from wastewater (especially from human urine) which would have been otherwise mixed in primary water sources creating eutrophication and algal blooms. These recovered nutrients can be a potential replacement for the chemical fertilizer in terms of economic feasibility and eco-friendliness. However, the adsorption of these inorganic nutrients using biochar has certain advantages over other methods like low-cost involvement, high efficiency, ease of operation, or less sludge production using minimal chemicals. The porous structure and the functional groups present at the biochar surface supports the adsorption of these nutrients, yet, the factors like pH and other coexisting ions affect the adsorption process significantly. Various modifications with metal salts/oxides increase the adsorption capacity by changing biochar's physical and chemical characteristics. Also, the recovery of adsorbed biochar is easy in case of modifications with metals like iron, however, these processes involve additional cost due to the use of chemicals. Since biochar is the carbon-rich product obtained through the thermochemical conversion of biomass under oxygen-limited conditions, the utilization of biochar for the recovery of phosphates and nitrates would serve as an appropriate carrier candidate in agroecosystems due to its various agronomical and environmental benefits. Nevertheless, before that, the bottlenecks of the resource recovery process should be addressed.

## Authors' contribution

PB has initiated the concept of the project. AP and JR have done the literature survey with detailed analysis of data compilation and interpretation. AP and JR have drafted the manuscript. PB has reviewed and finalized the manuscript. All authors read and approved the final manuscript for peer review and possible publication.

## 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.

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