Utilization of biochar for resource recovery from water: A review

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ABSTRACT

Over the past few decades, the shortage of water resource has prompted a shift in human concept about waste water: from waste to valuable resource. Utilizing wastewater can not only mitigate water scarcity, but also provide an opportunity for nutrient and energy recovery, further offsetting part of the exploitation of valuable resources. When establishing resource recovery systems of wastewater, the implemented technology and materials should be preferentially considered in order to achieve economically feasible and environmentally responsible solutions. The advantages of biochar in cost, nutrient retention and pollutant adsorption efficiency endow its possibility for resource recovery. Thus, understanding the relationship between biochar and resource recovery is essential to develop the applications of biochar in environment remediation and wastewater utilization. However, to this date there is no comprehensive review that establish the relevance between biochar and recycled substance. In this review, we aim to evaluate the roles of biochar in resource recovery from wastewater. Recyclable substances with the presence of biochar mainly include components, water resource and energy. Viable and effective methods for different recovered targets are classified. In particular, through revealing the interrelationship between biochar production methods and recovered substances, we try to provide the guideline for biochar selection. The re-application and value of recovered substances are also summarized comprehensively. Moreover, the current problems, existing limitations, and promising industrial application value of biochar in resource recovery from water are also put forward. This review can create awareness about the possibility of various options for resources recovery from water with biochar and contribute to further development and demonstration in wastewater treatment.

Keywords: Biochar; Resource recovery; Water; Substances; Reapplication

CONTENTS

1. Introduction

Water is critical resource used for urban, agricultural, and industrial purposes. However, the rapid development of global industrialization and urbanization makes the safe use of water and the maintenance of ecological stability a huge challenge. In reality, only a very small portion of water in the world is economically accessible for the above purposes. The shortage of water is a global problem threatening the entire biosphere and affecting the living of millions of people around the world [1]. Due to the contradiction between limited resources and the growth of resource demand, governments have realized the importance of energy-saving, emission reduction and sustainable development policy. Concomitantly, resource recovery from wastewater has attracted worldwide attention with its economical and ecological advantages. Considering the overutilization of freshwater from the natural ecosystem by industrialization and urbanization, water reuse and recycling are necessary and indispensable [2, 3]. Meanwhile, in order to address the challenge of resource scarcity in a sustainable way, it is clear that the forms of existing resources in wastewater should include not only clean water, but also nutrients, metal, and energy extracted from wastewater based on waste streams [4-7].

Water resource can be recovered from all scales and the treatment schemes of wastewater mainly depends on the water quality requirements of recycling water [3]. Nutrient recovery can be easily achieved with urine source separating technology and energy always recovered in the form of biogas which is prevalent in large-scale plants

[3]. Diaz-Elsayed et al. (2019) summarized wastewater-based resource recovery technologies across different scales. To date, it should be universally accepted that there is no single technology can perfectly achieve recovery of various resources for all scenarios. According to recovered resources, different technologies and approaches are considered and the trade-off is always seen. For example, high infrastructure costs and huge quality of energy is necessary in conventional activated sludge for energy recovery. Further, negative environmental impacts are usually accompanied with some effective technologies, such as the persistently release of environmental pollutants [8].

Zero-liquid discharge (ZLD) is considered an emerging technique to minimize waste and recover resources, and the core technology of ZLD is membrane-based technologies which are view as attractive future strategies. Membrane separation technology is the common water resource recovery technology at present stage, and various resources can be recovered if combined with other operation unit [9, 10]. However, membrane fouling and the decrease of membrane stability on account of salinity and substances build-up result in higher operating and maintenance costs. Pressure driven membrane processes along with intensive energy consumption is the limitation of wide application [11]. To reduce carbon emission, most researches focused on valorization and recovery leans toward utilizing inexpensive technology and reducing energy usage. Therefore, the technologies and methods for recycling resources from wastewater must be environmentally friendly, economically attractive, and can potentially recycle water, energy and a wide array of value-added components effectively.

In term of the existing technology and materials for resource recovery from water, the enrichment and separation effects of recycled substances are the critical indicators [8]. Strong capture capacity to various substances and hydrophobicity of biochar result in steadily increasing relevant researches about resource recovery with biochar. Moreover, biochar is generally resourceful and cost-effective because the feedstocks of it are mainly obtained from agricultural biomass and solid waste, and also contribute to reducing carbon emission [12]. Therefore, it is feasible to utilize biochar in resource recovery from water which becomes a big issue over time. However, the potential of biochar on resource recovery from wastewater, including sustainable mechanisms, subsequent treatment of biochar, regeneration methods of used biochar and the harvested substances has not been summarized. This review focuses on the role of biochar in resource recovery from wastewater and its final disposal. The aim of this paper is to: (1) explore the efficiency and mechanisms of biochar for resource recovery; (2) discuss the resource recovery methods after water treatment; (3) demonstrate the practical re-application of recovered resources; (4) arise interests of resource recovery from water using biochar; and (5) put forward the prospects of future researches in biochar-based resource recovery.

2. Resource recovery using biochar

Driven by the population growth and economic development, the consumption of energy, substance and water has steadily increased. This shortage of resources forced attention to resource recovery from wastewater. In the 1990s, researchers proposed that the traditional drainage system was replaced by the source-drainage system, which achieved separation of different types of sewage directly at the source [8]. Then, recovery and reuse of resources can be done accordingly, to these different partitions of the sewage.

Generally, sanitary sewage can be divided into three types: greywater, yellow water and brown water. Brown water contains excrement and rinse water, its high solid content makes it suitable for energy recovery through anaerobic digestion. Yellow water refers to urine sewage, which is low in carbon and high in nitrogen and phosphorus. It is mainly suitable for resource recovery and reuse of nutrients. Bathing and laundry wastewater is the largest source of greywater and important component of urban sewage, which accounts for more than half of the total water requirement [13]. But relatively low pollutants concentration in it increases the load of water treatment. This will be well discussed in following section.

A dramatic increase of biochar in water treatment has been investigated due to its superior properties, as well as its cheap price and widespread feedstock. The potential of biochar in resource recovery and the relationship between biochar and harvested substance are important aspects when it comes to recycling. Through summarizing the interrelationship between biochar and recycled substance in existing researches, the present review reveals the rule for biochar selection in resource recovery and puts forward guidance recommendations (Fig. 1). In the following section, the discussion of recovered substances will be divided among water, energy and components.

2.1. Components

2.1.1. Nutrients

Harvested nutrients loaded by biochar mainly consist of phosphorous, nitrogen and organic matter like humic acid. In traditional wastewater treatment plants, nutrients need to be removed as a part of contamination. However, the removal of contamination brings about the problem of sludge treatment, increasing the strain of resources and energy. At the same time, mineral scarcity, especially phosphorus shortage is always a severe problem for regulatory sectors and government [14]. So, it is necessary and urgent to develop the technology for recycling nutrients from wastewater.

Recently, separation of urine from other wastewater streams, namely source-separated urine, has gained increasing attention. Pharmaceutical removal is expected to be more effective in source-separated urine than conventional domestic wastewater. Moreover, urine contributes to more than 75% of total nitrogen and 50% of total phosphorus in wastewater. So recovering nutrients from urine can be regarded as a new resource recovery strategy [15]. Due to its high adsorption capacity, biochar was used to capture excess nutrients from wastewater which has become a central focus in environmental remediation studies [16].

2.1.1.1. Phosphorus

Phosphorus (P) is involved in almost all physiological chemical reactions and it is one of the most essential macronutrients for plant growth and development. Wastewater discharged from agriculture and urban activities are generally rich in phosphorus compounds, which is potentially the reason for eutrophication. The source of phosphorus available for production and life is minerals like phosphorite. Because phosphate rock resources are non-renewable, phosphorus recycling is of vital importance. Researchers have evaluated the effectiveness of biochar in P capture. Results showed that the capture capacities toward phosphate of biochar are usually determined by its physicochemical parameters [17-19]. These parameters can be accounted into two main sources: the biochar itself and the water to be treated.

Biochar produced by biomass feedstocks which are rich in metal like Al, Ca, Mg, and Fe (or their hydroxides) shows high efficiency when recovering phosphorus from aqueous solutions (shown in Table 2) [20, 21]. Biochar with high metal content can be produced by co-pyrolyzing natural minerals and pre-preparing with metal chloride solutions. For example, biochar with high Ca content can reduce the concentration of phosphorus in aqueous solution via the precipitation of Ca-P [22]. Li et al. proved that the capture capacity of P by biochar prepared by co-pyrolyzing with natural minerals can reach up to 207 mg P/g. The main mechanism for P capture was regarded as phosphate ion and its hydrolysates precipitate with Mg^{2+} or Ca^{2+} on the surface of biochar [23, 24]. Moreover, those basic oxides loaded in the biochar can also be a pH regulator [24]. In traditional phosphate precipitation methods for P recovery, the reaction pH is higher than the pH of natural water and rainfall [25], and additional chemical regents for pH adjustment are necessary. Therefore, the participation of biochar is particularly important as pH regulator. Besides, previous research has also proved that organic functional groups on biochar surfaces can be helpful for P capture, because electrostatic attraction between P and biochar was enhanced [26].

The existence of dissolved organic matter (DOM) is negative for P adsorption due to competition of sorption sites on the absorbents [27]. Marshall et al. showed that the P capture capacity of biochar increased from 16.9 mg/g to 37.5 mg/g when the pyrolysis temperature increased from 400 ℃ to 700 ℃ [25]. Since the pyrolysis temperature can influence the adsorption capacity of P by affecting the microstructure of biochar, such as porosity, mineral composition and functional groups, the relationship between pyrolysis temperature and phosphorus recovery efficiency is not significantly positive correlation [26, 28, 29]. Some studies only focused on the possibility and potential of phosphorus recycling by biochar under specific conditions, while actually biochar needs to be improved to adapt to its surrounding environment.

To summarize, there are several main mechanisms in recovering phosphorous from water (shown in Fig. 1): ion exchange or precipitation with strong chemical bonds, and surface deposition with weak chemical bonds [30]. Furthermore, precipitation was the dominant chemisorption mechanism for phosphate sorption onto biochar compared with other mechanisms [31, 32].

2.1.1.2. Nitrogen

The main forms of nitrogen (N) in water are ammonia nitrogen and nitrate nitrogen.

Ammonia nitrogen is a nutrient in water, which can be another aerobic pollutant leading to water eutrophication. Since nitrogenous fertilizer plays an important role in increasing crop yield and improving the quality of agricultural products, recycling nitrogen from wastewater can solve water pollution and resource shortage at the same time. Activated carbon and other carbon materials have proved their efficiency for nitrogen recovery, hence, biochar is a potential candidate for nitrogen recovery [33].

Removing ammonium nitrogen is a big challenge due to its wide occurrence. Obviously, pH is the first factor that needs to be considered when studying ammonium nitrogen removal, because ammonium nitrogen will transform into ammonia gas in strong alkaline wastewater, resulting in dissipation of recyclable component and air pollution [34, 35]. The ammonium nitrogen capture capacity of biochar will be enhanced with the existing metal ions dissolving from metal-rich biochar to solution, and the resultant prefer to co-precipitate on the surface of biochar. So the N maximum capture capacity of metal-doped biochar is higher than raw biochar, which shown in Table 1 and Table 2 [16, 31]. Therefore, compared to physical capture mechanisms such as ion exchange and electrostatic attraction, chemical capture mechanisms with the formation of new bonds might be the main pathway for N removal [16, 36]. However, the maximum capture capacity did not strictly increasing biochar concentration, the overlap of absorbent layers can shield available active sites [16].

In actual more complex wastewater environments, the absorption and recovery of N and P are always simultaneously taken into account [33, 34, 36]. In the study of Yu et al. (2020), biochar-mediated absorption - algal-bacterial system (BMA-ABS) method was used for nutrient recovery from swine wastewater with high-strength ammonium. The complex effects of biochar and algal-bacterial resulted in tremendous decrease of nutrients concentrations. And the recovery efficiencies of N and P are more than 95% [37]. Biochar possesses a good recovery capability when compared to traditional technology, efficiency of current implemented struvite recovery technologies found in wastewater is very low [38]. P concentration can be a limiting factor that determines the removal of ammonium [32]. Xu et al. demonstrated that when using magnesium chloride as pretreatment reagent, the maximum P capacity of biochar increased. When magnesium iron dissolved from biochar into the aqueous solution, magnesium ammonium phosphate (MAP) precipitation can be used as a mechanism to capture N and P simultaneously [34]. The dissociation degree of magnesium ammonium phosphate is low and part of it may be combined with biochar, therefore the possibility that nutrients are released back into the solution is slight [39]. And biochar with mesoporous and macroporous structure was hardly blocked by contaminants and biofilm when compared to granular activated carbon, which makes it more competitive for practical engineering applications [33].

2.1.1.3. Humic acid or humate

Humic acid (HA) or humate is a kind of macromolecular organic material widely existing in nature and a typical fraction of dissolved organic matter (DOM) in the eutrophic water body. In laboratory experiment, real water environment can be estimated with the addition of HA. It is an influencing factor when studying contaminant removal in aqueous solutions. And HA can prompt plant growth, recycling it from wastewater is meaningful [24, 40]. The capture ability and the maximum adsorption capacity of biochar for humate acid depend on surface charge, so pH becomes an important condition. In a study conducted by Li et al. (2018), biomass co-pyrolysis with natural dolomite powder showed that π-π interaction between the carbon matrix of biochar and HA may be the main mechanism for HA recovery [24]. Because HA can be regarded as a nutrient, while not considered separately, it is unnecessary to worry about the follow-up application and disposal since it can be recycled along with other nutrients.

2.1.2. Metal

Biochar plays an important role in repairing heavy metal polluted water, such as wastewater, coming from mines or industries. The ability and capacity of biochar to absorb heavy metal from aqueous solutions has been well discussed [41]. Because of the limited capture ability of heavy metal by the raw biochar, Wang et al. (2019) and Yang et al. (2019) summarized the mechanism and modification methods of biochar for heavy metal removal [42, 43]. Modification chiefly increases the functional groups of biochar and incorporate heteroatoms on carbon skeleton surfaces. The typical mechanism of recovery metal may involve physical adsorption, electrostatic interaction, ion exchange, surface complexation, and precipitation [41, 44, 45], but the specific role of biochar depends on the target heavy metal, absorbent and conditions of solution [43].

Xue et al. (2012) revealed that the increase of carboxyl surface functional groups attributed to the enhanced Pb capture capacity by the H_2O_2-modified biochar, so ion exchange is the main mechanism in this scenario [46]. Hu et al. (2018) reported that surface complexation reaction is the main mechanism for the increase of capture capacity of Cu-coated biochar with the formation of $CuReO_4$ or $Cu(ReO_4)_2$ complexes [47]. Xu et al. found that the mineral components of biochar played a much more important role than the carbon structure in recovering Pb(II). And the result showed that minerals control the Pb(II) capture through precipitation mechanism due to the smaller solubility product of $PbCO_3$, compared to that of $CaCO_3$ [45].

In previous studies, recycling methods are mainly aimed at biochar and non-metal elements. Heavy metal-enriched biochar would be a hazardous waste material since it can release heavy metal as secondary pollutants which pose an environmental risk challenge [42, 48]. Biochar can enrich heavy metals for the sake of recovery and it becomes a rich resource when used properly.

2.2. Water resource

The growing demand of water has triggered the use of unconventional water resources such as reclaimed water. Water is the main part of wastewater, and it can be one of the major recovered resources. Based on the concept of resource recovery, 'used water' can be the alternative of what was traditionally named 'wastewater' [49]. In areas where water resources are relatively tight, indiscriminately mixed drainage increases the difficulty of water reuse. Because the current approach of dealing with wastewater is mainly based on dissipating the non-aqueous molecules present, it is necessary to remove ‘contaminants’ from sewage treatment before discharge or following reuse [40].

Quality should be the judgement of recycled water rather than former use of water. Vast quantities of wastewater are produced in human production and life, especially the infinitesimal but various types of contamination with relatively low concentration in stormwater. So, the treatment and disposal of trace pollutants in stormwater needs to be considered carefully [50]. Because the excellent capacity of biochar to remove and retain organic matters, heavy metals and even pathogens indistinguishably, biochar shows the potential capacity in removing multiple contaminants from aqueous solution. So, biochar is an ideal material for water reuse and recovery (Fig. 2a) [41].

2.2.1. Stormwater runoff

Stormwater, upon dispose, can become part of the surface or groundwater, and it can also be used as landscape irrigation or industrial cooling with certain treatment (Fig. 2a) [44]. In some areas, storm water becomes valuable as freshwater resource in an arid area with government emphasis on resource utilization and reuse [51]. Particulate pollutants in stormwater runoff can be removed by physical processes such as sedimentation [52]. According to the relevant regulations and standards such as water quality standards for scenic environment use and the pollutants detected from real stormwater, many kinds of dissolved contaminants need to be removed before its reuse [51]. Trace organic contaminants [50, 51, 53, 54] like endocrine-disrupting chemicals (EDCs) [55] or antibiotics such as sulfamethoxazole [54], bisphenol A [56], bacterial

[57] especially Escherichia coli [56, 58-60], and N and P [21] were confirmed to be sorptive retention in the presence of biochar. To date, several researches show a decrease of the concentration of multiple contaminants in water treatment with the existence of biochar [21, 51].

Zhang et al. (2012) and Abit et al. (2016) showed that biochar produced with high pyrolysis temperature can reduce bacterial mobility (Fig. 2c) [39, 61]. Intermittent infiltration of stormwater maintained the dry and wet cycles of biochar in biofilters, which replenished and re-exposed surface attachment sites. But the existence of nature organic matter (NOM) may decrease the bacteria removal capacity of biochar on account of exhausting adsorption sites [57]. Therefore, it is necessary to test the stability and reactivity of biochar undergone weathering by abiotic and biotic aging and the deposition of organic matters and minerals [62].

In the construction of sponge city urban development, the government integrates stormwater biofiltration systems or biofilters to achieve urban stormwater recycling with urban construction or development plan [57, 63]. The composition of stormwater changes in different regions. In order to recover and reuse stormwater, the main contaminants and bacteria need to be removed. Biochar is usually used as an absorbent in traditional biofilter and can be an enhancement filter in a stormwater infiltration system for contaminant retention [53]. Plants and biochar mixing with sand or soil, which favored plant growth, is always included in these systems. In addition, the existence of biochar can provide habitats for microbial growth and enhance the further biodegradation of contaminants (Fig. 2b) [56].

In most stormwater infiltrations of green infrastructure (e.g. bioretention), the weakest retained contaminant, which is usually the first to experience breakthroughs, should be assigned as the most important index to monitor reliability and service life of biochar. In the pilot-scale biochar-amended bioreactor with the lowest biochar addition, the lifespan is longer than expectation [51, 64, 65]. In wastewater treatment plants, practical considerations such as clogging, plant growth and scheduled maintenance would likely be the limiting factors [51].

2.2.2. Urine/Yellow water

Urine is the main component of yellow water. In the previous section about nutrients recovery, urine can be regarded as a good source of nitrogen and phosphorus [3, 34, 66]. The constitution of urine is relatively simple compared with that of the industrial wastewater. The source of most of the nitrogen and half of the phosphorus in domestic water is urine, so the urine separation is considered an interesting method for simplifying nutrient recovery [38], and the rest of the aqueous solution also can be reused as water resource spontaneously. But the possible uptake of micropollutants found in human waste poses a barrier to the reuse of both nutrients via urine-derived fertilizers and water [67, 68]. Trace pollutants can be removed using multiple physical-chemical interactions which is well discussed in the previous section, moreover, cooperation with other chemical agents help accelerate the removal process [68-70]. There is a difference in pollutant adsorption between synthetic urine and real urine: the degree of freshness and hydrolyzation of urine are also the influence conditions. Some researchers [70, 71] proposed that the absorption driving force trend of biochar is van der Waals > hydrogen bonding > electrostatic interactions in removal of pharmaceuticals. The mechanism of removal is mainly dependent on the properties of biochar and contamination which are common to most sorbents (pH, temperature, feedstock, preparation conditions, presence of ions, humic acid, pharmaceutical structures, and functional groups) [72]. Modification of biochar can increase the pharmaceutical sorption capacity on biochar. For instance, the removal of polar compounds needs highly functionalized biochar for increasing hydrogen bonding interactions. Solanki and Boyer demonstrated that a high concentration of nitrogen and phosphorus in urine remained after biochar treatment. Their results suggested that biochar had the ability to remove pharmaceuticals while maintaining nutrient concentrations in solution for future use as a nutrient product [73]. Other authors emphasized the potential of biochar for pharmaceuticals removal, and how it can meet the requirements for water reuse through the treatment of combining various biochar [72, 74].

2.2.3. New trends

The heat-absorption capacity of biochar helps the application in photo-thermal transformation and shows the possibility for water resource recovery (shown in Fig. 3) [75]. Solar-driven interfacial steam generation is emerging as a green and sustainable technology for potential applications in water resource recovery. Xu et al. (2017)

revealed the hidden talent of mushroom biochar as low-cost material for solar steam generation (Fig. 3a) [75].Yang et al. (2019) used biomass *Enteromorpha prolifera* to construct biochar-based solar absorbers of the interfacial steam generators. The absorptance capacity of carbonized *E. prolifera* is high and over a wide wavelength result in high photothermal conversion efficiency of the generators over 80% under the sun (Fig. 3b) [76]. And Long et al.(2019) developed ethanol-treated-carrot biochar with the synergy of a high absorption to illumination and the presence of microchannels showed high evaporation rate of 2.04 kg/(m^2 • h) (Fig. 3c) [77]. Biochar is a new material in solar absorbers instead of costly materials like plasmonic metal particles and semiconductor. Generally, high light-to-heat conversion efficiency was obtained by carbonized surface, and inherent structure of biochar can enable sufficient water transportation [75, 77]. Although only few articles discussing thermal absorptivity and photothermal conversion capacity of biochar, biochar-based system can be used in sterilization, desalination, and water purification. Unique natural structure of biomass feedstocks retained during pyrolysis is the potential advantage of biochar as photothermal device material. To some extent, mass production of biochar can prompt real-world applications for water resource recovery.

Besides, Cuong et al. found that rice husk biochar can be used as electrode material in capacitive deionization (CDI), and biochar showed great potential for water resource recovery because of high inorganic ions removal capacity [78]. Although the charge efficiency and energy consumption of hierarchical porous carbon prepared from biochar need improvement when compare to previous researches [79], biochar still showed the possibility to achieve high-performance electrosorption in wastewater treatment. Moreover, CDI is frequently use for sustainable desalination of brackish water, so it is reasonable to assume that hierarchical porous carbon produced by biochar will increase strengthens competitiveness in cost and energy.

2.3. Energy

The main and most direct method to recover energy from wastewater is transferring volatile solids in sludge to biogas through anaerobic digestion (AD). Biochar can enhance the performance and stability of digestion process, and is considerable for the coupling of the biological and thermochemical conversion processes in the AD system (Fig. 4a) [80, 81]. Buck et al. (2018) and Chen et .al (2014) also provided that biochar can increase interspecies electron transfer between volatile fatty acid-oxidizing bacteria and hydrogenotrophic methanogens which was crucial for methane production (Fig. c and d) [82, 83]. AD is supposed to go through three sequential phases: (1) hydrolysis, (2) acidogenesis and acetogenesis, and (3) methanogenesis. The methane production is the last phase but the yield of energy production is highly correlated with all above phases. The influence of adding biochar in AD systems for biogas production will also discuss according to the sequence of these stages.

Overall, the existing biochar enhanced methane production in AD systems through stimulated the growth of correlative bacteria and activated important enzyme activity

[84]. Hydrolysis, as the first phase of the AD process, mainly refers to the conversion of macromolecule organic matter into soluble substances. Duan et al. (2019) indicated that biochar can disrupt cell walls of insoluble matter to increase the availability of digested sludge [85]. Biochar also showed positive impact in the hydrolysis phase through immobilization of degrading bacteria or enhancement and activation of important enzyme activity [81]. Volatile fatty acids (VFAs) is the main products of acidogenesis and acetogenesis phases and it is the precursor of methane. Biochar of certain proportion can result in higher VFAs production to increase the final methane concentration. Biochar also can through regulating the concentration of free ammonia (FA) or VFAs, reinforcing the buffer system in AD in order to reduce the toxic effects from large accumulation of VFAs [86]. Methanogenic phase is the limited speed for the entire anaerobic digestion process for AD of dissolved organic matter. Luo et al. found that biochar addition shortened the time before the methanogenic stage and raised the maximum methane production rate [87]. Moreover, with biochar added, the quality of biogas in AD system was upgraded, because the abundance of methanogenic microbes were promoted which was induced by biochar [88].

The influence of biochar prepared with different biomass feedstock in AD systems is summarized by Pan et al., and the vast majority of biochar used in AD system is raw biochar [81]. As stated above, the addition of biochar is beneficial for energy production and recovery through promoting each stage of progress, maintaining a stable pH, providing the appropriate environment for microbial growth (Fig.4b) [84].

3. Biochar modification for resource recovery

Methods of biochar modification are abundant, but it is hard to receive biochar with precisely pre-designable structures and tailored functionalities because the preparation process is not fully controllable. Most modifications can enhance specific surface and chemical properties, thereby enhancing substances recovery capacities [72] (shown in Fig. 5). Modification helps biochar become more competitive in water recovery, although due to the original biochar and target recovered resources, sometimes it is not necessary to modify biochar at all (summarized in Table 1). For example, the maximum recovery capacity of in-situ functionalization biochar derived from inherently other element-rich feedstocks is comparatively to modification biochar. Sludge and aquatic plants like water hyacinth are common feedstocks of in-situ functionalization biochar [16, 36, 56]. But in-situ functionalization biochar can be viewed as in-situ modified biochar in some ways [31, 39]. In the study of Fang et al. (2020), the types of biomass feedstocks have great influence on the modification effect, so the biomass feedstocks selection of biochar or in-situ functionalization biochar should be well considered before modification methods (shown in Table 1 and Table 2) [44, 89]. Examples of modified biochar for resource recovery are summarized in Table 2, and we will discuss according to classification of modification methods.

3.1. Modified with acid or alkali and oxidants

The capture capacity of biochar for different substances can be enhanced by using oxidants , which increase the number of oxygenated acidic functional groups (such as carboxyl, phenol base, quinonoid, lactone, and fluorescein) on the surface of biochar [42]. The process of modification can be achieved by adding acids, alkalis or certain oxidant reagents, in order to improve the surface functional groups of biochar. The specific surface areas, total pore volume and cation exchange capacity (CEC) of biochar were improved at the same time [23, 35, 42]. Biochar modified by oxidants may lead to considerable creation and enlargement of pore via carbon gasification in aqueous solutions [58]. Microstructure of biochar was enhanced through this modification method. HNO_3 or NaOH as modified reagent was used by Vu et al. (2017) to enhance the capture ability of biochar, with a large number of oxygen-containing functional groups introduced and the chemical characteristics of the sorbents surface improved. Results indicated that the N uptake capacity of the modified biochar was enhanced at least 2-fold [35]. And if alkali solution used to deal with feedstocks, which can efficiently remove lignin from lignocellulosic biomass, the enhancement of biochar properties may result from change of feedstocks composition [90]. Especially, H_2SO_4-modified biochar showed approximately double the specific surface area of original biochar, and also improved *E. coli* retention and reduced remobilization [58]. Ahmed et al. investigated the difference of biochar modified with different types of oxidants. The results confirmed that acidic modification generated extensive oxygenated functional groups, while alkaline modification produced high ratios of surface aromaticity and N/C [91]. Comparatively low concentration acid or alkali liquid can expose more adsorption sites by removing solubility matter or iron [21]. These variations improve the adsorption performance of biochar by increasing adsorption sites and/or strengthening the interaction force. Without bring other elements into biochar, this modification method decreases the environmental risk of biochar in utilization, re-application and disposal. The enhanced interaction between biochar and target substances is reversible, so desorption of substances can occur in different condition.

3.2. Per-treated with metallic solution or assembled with layered double hydroxides (LDHs)

Per-treating with metallic solution or assembling with LDHs is a familiar pretreatment method for metal doping of biochar with magnetic separation capacity. Additionally, the doped metal in biochar can contribute to the capture of target substance. For this modification method, biomass or pre-carbonized material, treated with metallic solutions, especially aqueous solutions of metal chloride, is used as the precursor of biochar material, which is primarily applied for nutrients recovery [34, 40, 92, 93]. Relatively homogeneous material can be prepared through this method since biochar can be dispensed equably in modification solution. When per-treated with metallic solution, the capture ability of modified biochar is three times as much as the raw biochar for N and P on average (shown in Table 1 and Table 2). Interestingly, Wang et al. found that the capacity of biochar for nutrient recovery enhanced if conditioned with Fenton's reagent, and the raw biochar pyrolyzed at 300 ℃ showed negative P removal efficiency [94]. Moreover, biochar modified with metallic solutions showed well recovery property at lower pyrolysis temperature and the influence of pyrolysis temperature on recovery performance is reduced [25, 93, 95, 96]. The interaction between harvested substances and biochar is not simply a physical effect, but a chemical reaction [25, 97, 98]. The difference between per-treating with metallic solution and assembling with LDHs could be the size of the materials used for recycling. LDHs construction shows comparatively order, stability, and good dispersion of colloidal increasing active site for adsorption [99]. Besides, anions such as phosphate radicals and nitrate radicals will be fixed to the interlayer of calcined LDHs when the original layered structure is restored in water [22]. The formation of M-O-P (metal-oxygen-phosphorus) accounts for high capacity for P capture [97]. Above all, it is obvious that the interaction between metal cation-mediated and functional groups on the surface of biochar can explain the excellent adsorption performance [26]. Alternatively, some biochar are soaked in ferrous chloride solution to get magnetic material, which will be discussed in the next chapter [100].

3.3. Co-pyrolysis with natural mineral

Co-pyrolysis with natural minerals such as ochre and dolomite is a kind of inexpensive way to produce biochar with light metal ions, especially Ca, Mg and Al. Natural minerals frequently used in modification are readily available, since they can be directly obtained from mine drainage treatment. Pyrolysis condition can change the solubility of mineral substance and its crystalline forms. The composite material is metallic oxide hybrid carbon which presents the ability for nutrients recovery.

Precipitation, electrostatic attraction, and π-π interaction are important mechanisms in recycling depended on the biochar's surface properties [24, 26]. The addition of ochre into the feedstock not only improves P recovery properties, but also produces biochar which comply with guidelines relevant to possible future regulation of biochar application to soil. Biochar produced by 1:1 mixture of anaerobically digested sewage sludge and ochre increased the maximum capture capacity by approximately 30% from K_2HPO_4 solution [101]. And in the study of Li et al. (2018), biochar produced by co-pyrolysis with dolomite recovered 7 times P capture capacity than that of raw biochar. And the HA recovery capacity also slightly increased with modified biochar [24]. However, in Mosa et al. (2020) study, biochar-supported natural zeolite composite shown slightly decrease of P and HA capture ability when compared to raw biochar's. The relatively high desorbability, stability and renewability potentials of biochar is helpful and valuable for subsequent progress, so modification for biochar is necessary [102]. Because biochar are similar to what is obtained through modification, this method is comparable with above section in some ways.

4. Resource recovery methods after water treatment

Biochar with low solubility is easy to separate from aqueous solutions in laboratory experiments. The ability and purity of separation and purification determine the subsequent use-value. In large scale experiments and engineering, the operability of recovery methods is worth considering. It is necessary to evaluate various recovery methods to meet the different demands of the final disposal for harvested substance. In the following sections, several recovery and separation methods which classified through recyclable material for nutrients, metal and water resource will be discussed. And due to the different characteristic of recovered substance (methane) and treatment system, energy recovery method is just simple collection (shown in Fig. 6).

4.1. Magnetic separation

On the one hand, magnetic biochar with different resources pretreated with iron particle-containing reagents like $K_2Fe_2O_4$ and $FeCl_2/FeCl_3$ can be easily separated by a magnet [17, 100, 103-105]. On the other hand, iron-rich raw materials like municipal sewage sludge or plant residues which already accumulate Fe ion can be used to prepare magnetic biochar by direct pyrolysis [106]. Zhang et al. tested the saturation magnetization value of biochar prepared by $K_2Fe_2O_4$ solution, and the numerical value changed from 57.9 emu/g to 45.2 emu/g after usage which indicated no significant change in the magnetic separation ability for recovery [103]. The magnetic force is extensively utilized in batch experiments on the laboratory level, but hardly appeared in industrial application. However, an external magnetic field can be manually adjusted for engineering operations. This shows the potential of magnetism in real applications [106].

4.2. Membrane or filling material

The addition of activated carbon has proved to be effective on membrane bioreactor processes for wastewater treatment and water reclamation [107]. Therefore, biochar, with the advantage of the low-cost and abundant source, can be applied in wastewater treatment processes. In water treatment, biochar is increasingly used as a filling material in mixed matrix materials [108]. Moreover, particle size of biochar is relatively large, which is easy to separate with membrane. In this method, the recycle ability of biochar and separation degree of solid and liquid phases are increased through altering the dispersion of biochar. The application of biochar in biofilter is a good example [50]. The combination of biochar and membrane bioreactor has benefits of slowing down the membrane fouling in following progress and enhancing the life cycle [109]. Biochar became one part of construction or processing link instead of just being evenly dispersed in water, there is no need of a subsequent separation step.

4.3. Calcination

Calcination might be an emerging technique for metal recovery. Burning biochar in air under temperatures lower than 500 ℃ will remove carbon matrix and other reserved non-volatile substances [103]. In a study conducted by Xu et al. (2017) [45], waste-art paper biochar with high contents of fillers/adhesives was used to capture Pb from water. The maximum sorption capacity was about 1.5 g/g, which was significantly higher compared with previous research. The used biochar mentioned above was incandesced in a muffle furnace at about 350 ℃, which helps the captured Pb(II) on biochar transfer into nano-PbO with high purity (more than 96% (wt%) of the ignition residue). With nanostructures, the outcome is a high-value product and can apply in storage batteries production and other manufacturing [110]. To date, there is not too much research dealing with biochar in this way for recovery substance, calcination still remains a possibility for recycling various components considering its simplicity and operability. However, the emission of exhaust during calcination is regard as a new pollution source. The generation of dioxin and PAHs which are the by-products of calcination show serious impairment to environment and human health. And the advantage of biochar in carbon sequestration is eliminated.

4.4. Solvents for extractions or elution

Using solvents for extracting or eluting substance from biochar originally aims at retaining and reusing biochar [45]. The target harvested substances are concentrated in solvent for further use. Solvents for eluting biochar after recycling plant growth-related nutrients can be used to produce nutrients solution. In Jiang et al. (2018) study, 3M NaOH for biochar regeneration after P recovery and biochar samples can be used at 5 times [96]. The rare metals in extraction liquid can be recovered through adjusting pH or adding precipitants [47, 111, 112]. 100% of Pb(II) can be recovered by 1mol/L HNO_3 and more than 90% of captured Re(VII) can be recovered by 0.1mol/L KOH after four cycles from different biochar [45, 47]. Although the remained eluent is easier to deal with after reduction if it is not possible to regenerate them, the secondary pollutant of solvents should be well considered.

5. Practical re-application of recovered substances

Some laboratory studies and pilot-scale have demonstrated the potential and possible benefits of biochar for resource recovery from wastewater. The re-entrance of the separated substances into material circulation and energy flow of the ecosystem minimizes the adverse impacts on the environment. According to the current researches, the practical re-application of recovered substances can be summarized into several parts.

5.1. Fertilizer

There is increasing interest in rehabilitating low fertility soils to improve crop yield and sustainability with the re-application of biochar harvested by nutrients. and the selection of appropriate biochar must be made by taking the soil type and target crop into consideration (Fig. 7a and 7b) [113]. The possibility of biochar after recovering nutrient used as soil improver can be evaluate by water extractions which estimates soil pore water and plant growth experiment in laboratory experiment [26]. And Shepherd et al. confirmed the possibility of biochar for phosphorus recovery by theoretical calculation [101]. The reasons for why applying reclaimed biochar can increase the growth of crop are the improved soil CEC and organic matter, which meant that nutrients were retained and nutrient leaching was reduced [114]. To date, several studies have shown that the interactions between P and biochar lattices were not strong enough to prevent P releasing into the environment [101, 115, 116]. It provided a possible way that biochar rich in nutrients could be a kind of green and applicable fertilizer which also can be the alternative to industrial manure and inorganic fertilizer [26, 31, 100]. In addition, the application of biochar after capturing nutrients can slow down the exploitation of phosphorite and reduce the pollutants released into environment by fertilizer production. Liu et al. (2019) considered that recovered biochar with flower-like precipitation $Ca_5(PO_4)_3(OH)$ can be used as a high value-added fertilizer [90]. The potential of biochar used as P supplement depends on P species. Biochar made from animal bones with these two forms of P (HydAp and OctaCa), is hardly utilized than other biochar rich in other P species, since the bioavailability of Ca-P is much lower than Fe-P and Al-P [117, 118]. Li et al. revealed that the average growth height and fresh weight of a plant prominently increased with only 1% added biochar [24]. Wang et al. proposed that biochar after nutrient recovery shown the ability for promotion of seed germination rate and increasing of grass shoot length [94]. Xu et al. also demonstrated that the application of nutrient-enriched biochar (NBC) after wastewater treatment improved the height and biomass production of plants. There was no significant difference between NBC and inorganic fertilizer for enhancement of the dry matter production [34]. Biochar could be used as a slow-release fertilizer or soil amendment [28, 102], and the relatively high nutrient release in the initial stages matches the plant growth curve well [101]. The function of biochar as a supplement when added to different types of soil is concluded by Yu et al. [114]. Not only N and P, humate acid, as important chemical fertilizers and plant growth promoters, can also be captured and enriched from water [40, 92]. Biochar may also accelerate the composting process and improve composting quality before end-product is applied to soil (Fig. 7c) [21, 113]. However, according to the different biomass precursors and previous use, the potential toxicity need to be assessed before industrial application [101].

5.2. Miscellaneous urban water or supplement for surface water

The purpose and final requirements of water treatment depends on the corresponding functions of water and its quality standards. Different demands of water, like water for urban greening irrigation, industrial condensation, agriculture irrigation or drinking, determine the corresponding treatment conditions and complexity of the process (Fig. 7d and 7e). Across all scales, non-potable reuse (NPR) is the most prevalent application for water reuse [3]. Recycled water is available to municipal, industrial, and agricultural activities if only up to appropriate water standards [58]. With long-term monitored systems set up and treatment methods cooperated, effluent treated by biochar can even reach the standards of fresh water or even drinking water.

5.3. Capacitor or catalyst

Various carbon materials can improve their electrochemical performance with a certain amount of metal [119, 120]. Biochar can be used as the electrode filling material or catalyst carrier after retreatment like microwave treatment or pyrolysis [121, 122]. During retreatment, biochar and recovered metals complement each other, and the presence of metals improve the catalytic performance of biochar. Biochar plays multiple roles in catalysis: it not only enhances the conversion of tar during the pyrolysis process, but also converts high-valence metals to a low-valence state, further improving catalytic characteristics. Biochar adhering particular metal has a high potential for the replacement of more expensive synthetic carbon nanomaterials, such as carbon nanotubes, for future supercapacitors, biomass gasification tar removal, and syngas conditioning [42, 123].

5.4. Industrial production and use

Industrial secondary operation is based on the security risks of direct application and improvable products quality. For instance, due to the restriction of contact time or efficiency in water treatment, the amount of substance adhere to biochar may not be up to the standard of soil fertilizer. Manual improvement and additive to meet requirements become a good strategy, which means industrial production and improvement should be considered [117]. We must establish a highly industrialized configuration and complete local distribution channels. Incineration biochar for power generation can be the simplest disposal way of biochar after different utilization [8]. Moreover, compared with original biochar, burning biochar that has adsorbed organic matter with increased calorific value is a valid treatment to deal with hazardous waste. Building and engineering materials can be another consideration for the used biochar after separation and recovery.

6. Conclusion and outlook

The increasing resource demand and the emerging challenges for wastewater treatment plants have motivated the implementation of resource recovery [3]. This review highlights the role of biochar from the perspective of resource recycling. Biochar shows its application potential in resource recovery from water, and the subsequent treatment and disposal are promoting circulation of various aspects. The utilization of biochar can reduce resource recovery cost and energy usage. Therefore, application of biochar-based materials for resource recovery is feasible and potential, but there are some existing problems that need further discussion and exploration.

6.1. More research on modification methods of biochar

Until now, modification methods of biochar for resource recovery is relatively simple and when compared to biochar used in other areas like energy storage. Because of value added with recovered resource, the cost in biochar modification can be offset. More intricate modification methods should be attempt in producing biochar. Besides, in previous discussion, chemical reagent especially including metal ion can increase some resource recovery capacity. However, the problem of metal leaching and materials stability may far away from cleaner and green production principle, and it will put stress on the following management. In-situ modification and functionalization of biochar which result from the selection of biomass feedstocks can reflect the advantage of biochar in price and source. Moreover, the direction of garbage classification can guide feedstock selection of biochar, and biochar is valuable product from waste treatment and disposal.

6.2. Transfer from the batch experiment, pilot to biochar-based systems for treatment

Most researches only investigated the feasibility of biochar for resource recovery from water under laboratory conditions. To date, more and more pilot-scale device constructed by biochar were discussed. However, due to prospects, constraints, risks, and uncertainties on biochar and its applications, the design optimization of biochar-based systems for the treatment of drinking water and wastewater remain largely unexplored. On the one hand, the difference of the initial state of raw material in laboratory experiments and engineering application should be taken into account. During the collection of agriculture wastes like straw, which are comparably simple or pure, the existence of impurity or inert substance such as plastic film is inevitable. Mixing in plastic, biochar production progress may bring dioxin-like compounds which result in atmospheric pollution. Besides, the interaction between biomass and impurity may led to uncontrollable properties of products. Meanwhile, the biomass is always grinded into small particles and washed several times in laboratory while it is not feasible for engineering production because of extra energy consumption and costs. Moreover, the shape of raw material can influence the contact surface during pyrolysis. So, the property and effects of biochar may be discrepant in laboratory preparation and factory production. On another hand, when dealing with complex actual water bodies and changing requirements, a large number of environmental factors should be considered. For instance, the effective removal of microplastic or nanoplastic as emerging pollutants using biochar, or the biotoxicity of biochar in size will take a lot of time and energy to optimize to the level of industrial application [124-126]. Clearly, further research based on biochar is bringing laboratory scale research to full-scale applications and promoting practices from source recovery-intense regions to other locations.

6.3. Regional water circulation and material recycling

There is an increasing recognition for water-energy interaction in resource recovery from water. Water and substance recycling should not be the target but rather become part of the material and energy cycle. Fig. 8 presented that wastewater treatment and resource recovery from water is the core phase and intersection of water circulation and material recycling. Due to the restriction in economy, policy and other effects, recovery methods and technology should be appropriately to the local setting and context at first [8]. So, it turns out that combination of related industries will transform linear material flows into looped material cycles. Nature elements of geographical factors like terrain, climate and soil can affect the living styles and eating habits of the region. In order to cater local needs and development, the selection of biomass can combine with solid waste management. Moreover, regional circulation means biochar should be produced and used near the site of application or near biomass sources [41, 54]. For instance, the easiest implementation of urine source separation using biochar in urban is composting toilets for use on a local lawn or garden [3]. And relatively high concentration of N and P can be recovered to be soil manure.

Because of the restriction of different types of water requirement, biochar-based treatment is necessary to co-operate with other technologies and methods. But the recovery should be established on applicable water supply and drainage systems, perfect management facilities, and complete knowledge or technology of using biochar.

From the collection of the biomass feedstocks to the practice and recovery process of biochar and relative substances, the integral life cycle assessment (LCA) need to be evaluated and estimated. The cost of cycling can be reduced through the utilization of biochar, but when choosing between decentralized management or centralized treatment, there are still more to be considered.

6.4. Combined with an urban water supply and drainage systems

Wastewater is regarded to generate when the quality of water for non-consumptive use degrade [49]. The low efficiency and low coverage of the water recycling systems in urban construction, like rain and sewage which is not classified when recycling, along with the limited nature of freshwater resources, pose challenges for sustainable development and threatens human water security. Taken greywater as an example, it mainly refers to bath washing and laundry sewage and is an important part in municipal sewage. Greywater is characterized by large water volume and low pollutant content, so it is another representative source which is also suitable for water reuse.

Low impact development (LID) systems, a technology developed in the late 1990s originally used for storm runoff management and non-point source pollution treatment is increasingly used to manage wastewater [44]. Through decentralized, small-scale source control of wastewater, the application of LID brings the developed area close to natural environment. Specific and representative construction of LID including underground storage and permeable road and green roof. Biochar can be used as substrates amendment and replace traditional filling material of LID [127], and the application of biochar not only can reduce the cost, but also increase maintainability and operability of LID. In addition, adaptation measures to local conditions should be also reflected in the construction of the new and old towns. In some specific areas, stormwater is currently collected and discharged into receiving water bodies via separate drainage systems. While in new town construction and development, the adoption of LID approach used as an alternative to traditional stormwater drainage design can potentially be harvested for non-potable uses. Large-scale and biochar-based field demonstration tests and long-term operational monitoring are required to provide assurance that system performance and water quality standards are being continuously met, as well as to identify requirements to maintain the longevity of the control device for water recovery [51].

6.5. Holistic view in resource recovery

A schematic view of resource recovery with biochar involvement is provided in Fig. 9. The progress of using biochar to recycle resources from water requires certain inputs and results in certain outputs. Establishment and publication of regulations are of importance in the field of resource recovery. Uniformity and justification in resource recovery will be easily obtained and promoted by guidelines and law. Meanwhile, top-down implementation and management method may reduce the conflict between different sectors. Clearly, rules and definition of resources recovery should be well considered. For example, the source and production methods of biochar, recyclable resources using biochar and reapplication of recovered resource should be detailed in legal frameworks. Public participation and cooperation in legislation about resource recovery will increase public confidence and public acceptance of recovered products [3]. Promotion of successful case and good practice in resource recovery with biochar can also improve acceptance of recycling among people. And appropriate policies will encourage and prompt the overall education, research and development. Resource recovery cannot just regard as a technology but needs to be viewed in a holistic manner [8]. Besides, the input illustrated in Fig. 9 can be viewed as the barrier and limitation in resource recovery with biochar. In order to promote and popularize the application of biochar for resource recovery, some subsidies might be given from country and government. In long term, positive and favorable outcomes of resource recovery is necessary to ensure stable and sustainable development. Besides, the profits of overall progress are also necessary.

Overall, biochar exhibits the possibility of resources recycle from water. The prospects for further research into wastewater-based resource recovery systems are positive with the development of water quality monitoring. Biochar with low economic and environmental footprint can bring about more meaningful and successful implementation of demonstration and full-scale projects. As for a rising material widely used in water, the long-term influence of biochar before and after use requires more effective and reliable information. Moreover, to achieve stable and sustainable resource recovery from water, biochar should be regarded as a technology as a part of the recycling process instead of material used in resource recovery.

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Table 1. The application of raw biochar in resource recovery.

Biochar feedstocks	Pyrolytic condition		Recovered substance	Source of wastewater	Recovery capacity	References
	Temperature	Time				
Wood cuttings, rice husks	600 ℃	10 h	N	Piggery manure anaerobic digested slurry	44.64 ±0.602 mg/g, 39.8 ±0.54 mg/g	[16]
Grapevine canes	400 ℃, 500 ℃, 600 ℃, 700 ℃	1 h	N	Synthetic solution (containing Ca^{2+})	16.9 mg/g, 25.9 mg/g, 32.0 mg/g, 37.5 mg/g	[25]
Brewers spent grain (Mg enrich) and Sewage sludge (P enrich) (80:20 wt%)	400 ℃, 500 ℃, 600 ℃, 700 ℃	2 h	N	NH_4^+-N solution	31.1 ±0.2 mg/g, 34.1 ±0.3 mg/g, 41.9 ±0.3 mg/g, 34.6 ±0.2 mg/g	[39]
Wood, rice husk	600 ℃	10 h	N	Piggery manure anaerobic digestate slurry	44.64 ±0.602 mg/g 39.8 ±0.54 mg/g	[16]
Wood, corncobs, rice husks, sawdust	600 ℃	10 h	P	Anaerobically digested liquid swine manure	7.67 mg/g, 6.43 mg/g, 5.73 mg/g, 5.41 mg/g	[128]
water hyacinth *(Eichhornia crassipes)* growing synthetic contaminated water	450 ±5.0 ℃	2 h	P	KH_2PO_4 solution	31.55 mg/g (Fe^{2+}), 22.03 mg/g (Zn^{2+}), 16.81 mg/g (Cu^{2+}), 12.17 mg/g (Mn^{2+}), 12.15 mg/g (contract) The contents in () means the addition ions during the growing of water hyacinth	[31]
Fungal biomass (growing backwash diluted with primary effluent wastewater)	700 ℃	/	P	Sodium phosphate solution	23.9 mg/g	[129]
Brewers spent grain and	450 ℃,	2 h	p	K_2HPO_4 solution (with 3-(N-morpholino)	0.95 ±0.18 mg/g,	[26]

Sewage sludge	550 ℃			propanesulfonic Acid (MOPS))	0.95±0.23 mg/g	
Wheat husk (purchase)	/	/	N, P	Urine	/	[38]
Lodgepole pine wood	1000 ℃	1 h	N, P	Real industrial wastewater	1.0 mg/g and 3.6 mg/g	[33]
Cacao shell or corn cob	350 ℃	3.5 h	N, P	NH_4NO_3 or K_2HPO_4 solution	3990 ±138 mg P/kg and 697 ±23 mg N/kg	[36]
Coconut shell, bamboo, Southern yellow pine, and northern hardwood.	/	/	Water resource (removal pharmaceutical)	Synthetic urine		[73]
Wood dust	300 ℃, 500 ℃ and 700 ℃	6 h	Water resource (removal bisphenol A)	Stormwater runoff		[56]
60% Monterey Pine, 20% Eucalyptus, 10% Bay Laurel, 10% mixed hardwood and softwood	180-395 ℃	6 h	Water resource (removal fecal indicators and nutrients)	Natural stormwater		[130]
Wood chips (purchase)	350 ℃ and 700 ℃	/	Water resource (removal *Escherichia coli*)	Synthetic stormwater		[59]
Biosolids primary, dissolved air floatation thickened solids, digester sludge, secondary digester sludge, human fecal material	850 ℃	2h	Water resource (removal sulfamethoxazole)	Surface water, stormwater, and wastewater effluent		[54]
Waste-art-paper	300 ℃, 450 ℃ and 600 ℃	2h	Metal (Pb(II))	Pb(II) solution	1555 mg/g (600 ℃)	[45]
Purchase	/	/	Water resource (removal nitrate, metals and trace organic contaminants)	Urban runoff		[51]
Pinewood (purchase)	/	/	Water resource (removal trace organic contaminants)	Synthetic stormwater		[50]
Wood (purchase)	/	/	Water resource (removal trace organic contaminants)	Synthetic stormwater		[53]
Not mention	/	/	Water resource (removal bacterial, pathogen and	Synthetic stormwater		[60]

			coliphage)			
Southern Yellow Pine	550 ℃	/	Water resource (removal nitrate)	Stormwater		[131]

Table 2. Relationship between biochar modification conditions and resource recovery.

Modification methods	Biochar feedstocks	Pyrolytic condition Temperature	Time	Recovered substance	Source of wastewater	Recovery capacity	References
1M H_3PO_4 / 10% H_2SO_4 modified or 0.1M KOH modified	Forestry wood waste	700 ℃	15 h	Water resource (removal *Escherichia coli*)	Synthetic stormwater		[58]
HNO_3	Corncob	400 ℃	1 h	N	NH_4Cl solution	22.6 mg/g	[35]
2 M solution of NaOH or 1M HCl	Coal fly ash	/ (produce temperature is about 1140 ℃)		P	KH_2PO_4 solution	57.14 mg/g	[23]
$MgCl_2$ solution	Sugarcane harvest residue biomass	550 ℃	1 h	P	Phosphate aqueous solutions	121.25 mg/g	[100]
$MgCl_2$ solution	Ground corn	300 ℃, 450 ℃, 600 ℃	3 h	P	Swine wastewater	232 mg/g, 233 mg/g, 239 mg/g	[95]
$MgCl_2$ solution	Moso bamboo (*Phyllostachys pubescens*)	400 ℃, 500 ℃, 600 ℃	1 h	P	Phosphate aqueous solutions	344 mg/g, 357 mg/g 370 mg/g,	[96]
20 wt% $MgCl_2$ solutions	Cypress sawdust	600 ℃	/	P	KH_2PO_4 solution	66.7mg/g	[28]
2.0 M $MgCl_2$ solution	Corn straw	550 ℃	1h	N, P	Swine wastewater	33.16 ±0.52 mg N/g and 3.22 ±0.34 mg total P/g	[37]
2.3 M $MgCl_2$ solution	Wood waste and *Sophora japonica Linn*	600 ℃	/	N, P	Human urine	47.5 mg N/g and 116.4 mg P/g	[34]
1.25 M $MgCl_2$ solution	Rice husks	450 ℃	2 h	N, P, HA	Synthetic solution (20 mg/L humic acid, 60 N mg/L, NH_4Cl and 60 P mg/L KH_2PO_4; pH=8.0)	58.20 N mg/g, 125.36 P mg/g, 34.57 HA mg/g	[40]
$MgCl_2$ solution	Sugarcane crop harvest residue	550 ℃	1 h	N, P, HA	Livestock wastewater	22 N mg/g, 398 P mg/g, 247 HA mg/g	[92]

$MgCl_2$ or $CaCl_2$ solution	Ground corncob	300 ℃, 450 ℃, 600 ℃	3 h	P	Biogas fermentation liquid	294.22 mg/g, 315.33 mg/g, 326.63 mg/g	[93]
$MgCl_2$ and $CaCl_2$ solution	Peanut shells, sugarcane bagasse	400 ℃, 700 ℃ and 850 ℃	1 h	P	Acid-extracts solution of incinerated sewage sludge ash (pH<2)	11.80 mg/g (700 ℃), 129.79 mg/g (700 ℃)	[89]
$Ca(OH)_2$ solution	Straw (powder)	600 ℃, 700 ℃, 800 ℃	2 h	P	Phosphate solution	97.4 mg/g, 166 mg/g, 197 mg/g	[90]
$AlCl_3$ solution	Poultry manure and garcane straw	350 ℃, 650 ℃	/	P	Synthetic eutrophic water	701.65 mg/g (powder) and 356.04 mg/g (fragment), 758.96 mg/g (powder) and 468.84 mg/g (fragment)	[132]
Fenton's reagent (110 mg Fe (II)/ g volatile solids (VS) and 88 mg H_2O_2/ g VS)	Raw sludge	300 ℃, 500 ℃, 600 ℃ 700 ℃, 800 ℃	2 h	P	KH_2PO_4 solution (46 mg P/L) with 1.2 mol/L of Cl^-, NO_3^-, and HCO_3 added and the liquid phase of anaerobic digestate	1.843 mg/g (300 ℃)	[94]
$FeCl_3$ solution	Biomass (not mention), fly ash and biomass, coal gangue	500 ℃	/	P	KH_2PO_4 solution	2.39 mg/g, 3.08 mg/g, 3.20 mg/g	[20]
0.8 mol/L $FeCl_3$ solution	Ground corn straw	500 ℃	3 h	P	Biogas slurry	220 mg/g	[133]
$FeCl_3$ (Fe/C w: w = 0.70)	Rice husk	500 ℃	/	Water resource	Stormwater runoff		[21]
0.05-0.5M $Al_2(SO_4)_3$ solution	Purchase	285 ℃	/	Water resource (removal Arsenic)	Real stormwater runoff		[134]
$FeCl_3$ and $FeSO_4$ solution	Douglas fir	Not mention	/	Metal (Pb and Cd)	$Pb(NO_3)_2$ and $Cd(NO_3)_2$ solution (pH=5)	40 Pb mg/g and 16 Cd mg/g	[135]
$FeCl_2$ and $FeCl_3$ solution	Camel bones	500 ℃	2 h	Metal (Pb (II), Cd (II) and Co (II))	$Pb(NO_3)_2$, $Cd(NO_3)_2$ and $Co(NO_3)_2$ solution	344.8 Pb mg/g, 322.6 Cd mg/g, 294.1 Co mg/g	[136]

0.2 M cupric acetate monohydrate solution	Bamboo shoot shell	500 ℃	4 h	Metal (Re (VII))	$KReO_4$ solution (pH=1)	10.2 mg/g	[47]
Zinc acetate dihydrate (8 mmol) (1 M HNO_3 pre-treated)	Bamboo shoot shell	550 ℃	3 h	Metal (Re (VII))	$KReO_4$ solution (pH=1)	24.5 mg/g	[137]
Layered double hydroxides Mg/Al	Sugarcane leaves	550 ℃	1 h	P	KH_2PO_4 solution (pH=3)	81.83 mg /g	[98]
Layered double hydroxides Zn/Al	Stalk	600 ℃	1 h	P	K_2HPO_4 solution	152.1mg/ g	[97]
Co-pyrolysis	Anaerobically digested sewage sludge and ochre	450 ℃, 550 ℃	0.5 h	P	K_2HPO_4 solution (with 3-(N-morpholino) propanesulfonic Acid (MOPS))	1.24 ± 2.10 × 10^{-3} mg/g, 1.26 ± 4.66 × 10^{-3} mg/g	[101]
Co-pyrolysis	Sawdust and dolomite	400 ℃, 550 ℃, 750 ℃, and 900 ℃	1 h	P, HA	Actual wastewater	207 mg P/g and 469 mg HA/g (900 ℃)	[24]
Co-pyrolysis	Water hyacinth and zeolite mineral	450 ℃	2 h	P, HA	K_2HPO_4 solution or humate ($CH_8Na_2O_4$) solution	11.53 mg P/g and 8.51 mg HA/g	[102]

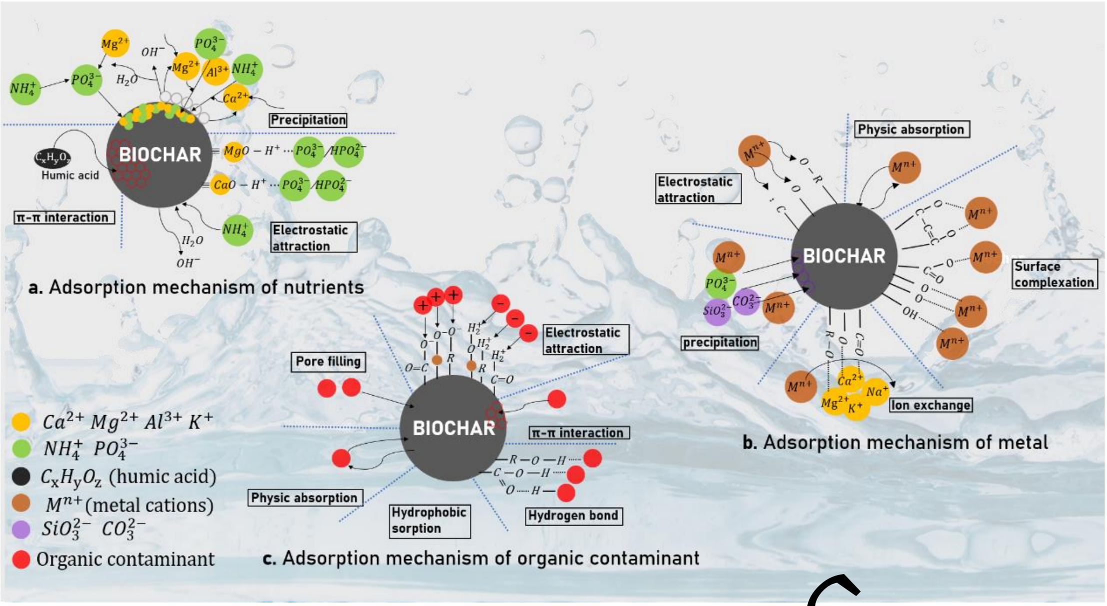

Fig. 1. The mechanisms of (a) nutrients recovery, (b) metal recovery, and (c) organic contaminant (such as antibiotic, PAHs and PAEs) removal by biochar with the goal of water resource recovery.

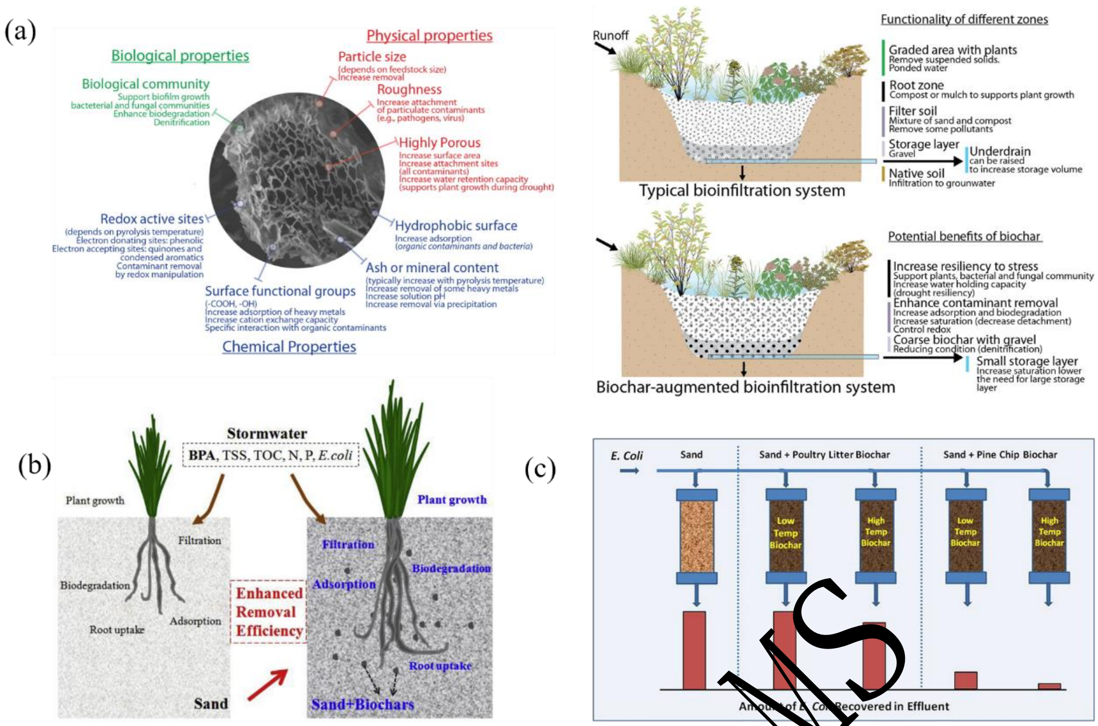

Fig. 2. The potential of biochar for water resource recovery. (a) Properties of biochar for removal of contaminants from stormwater and potential functions of biochar at different region of bioinfiltration system [54]; (b) Schematic diagram of the enhanced stormwater contaminants removal by biochar-amended biofilters [56]; (c) Biochar can effectively retain *E. coli* [61].

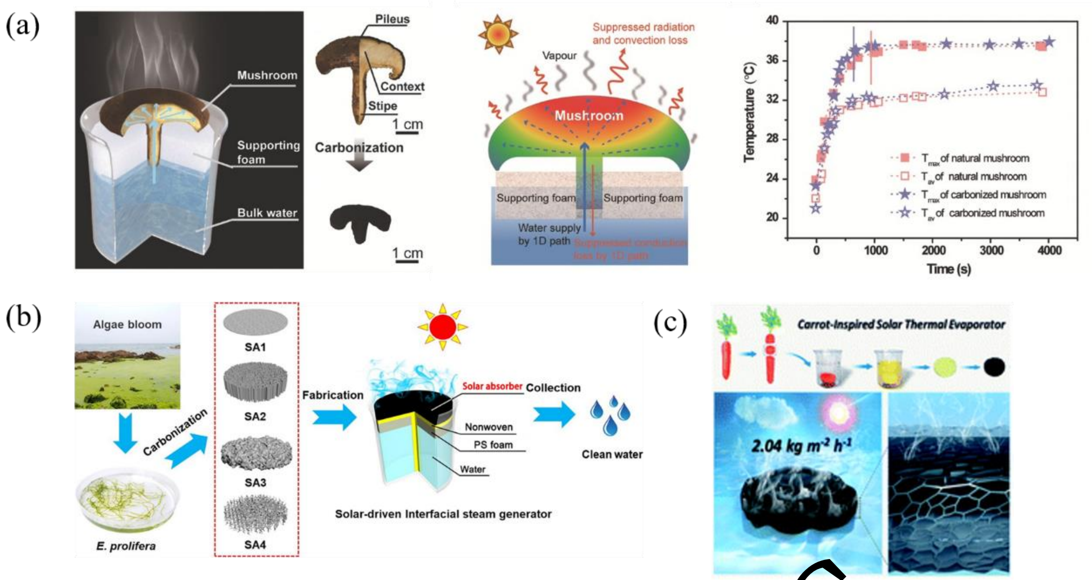

Fig. 3. New trend of utilizing biochar in water resource recovery. (a) Heat behavior of solar steam generation with mushroom-based biochar [75]; (b) Schematics of the design concept, structures of the biochar-based solar absorbers, and a configuration of the solar-driven interfacial steam generator [76]; (c) carrot-based biochar used as solar thermal evaporator showed high evaporation rate under one-sun illumination [77].

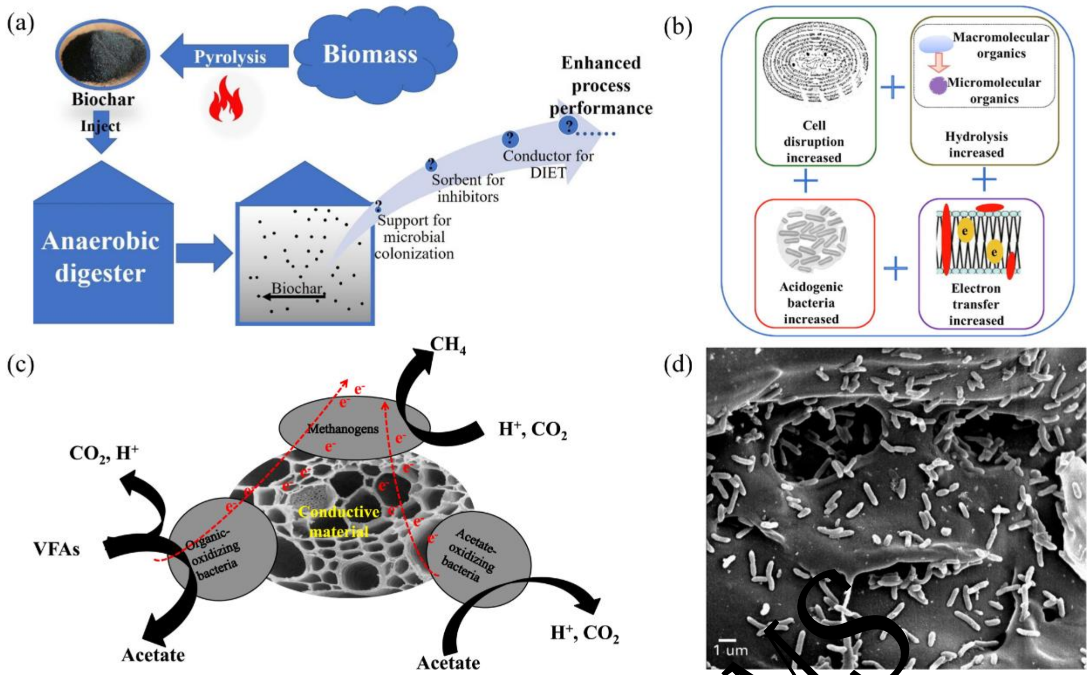

Fig. 4. The role of biochar in AD system for energy recovery. (a) Concept diagram of the application of biochar in anaerobic digestion [81]; (b) positive effects of biochar in AD [85]; (c) Mechanisms of biochar-mediated direct interspecies electron transfer (DIET) [84]; (d) Scanning electron micrograph of one of the biochar tested (BEC) with a syntrophic co-culture of *G. metallireducens* and *G. sulfurreducens* [83].

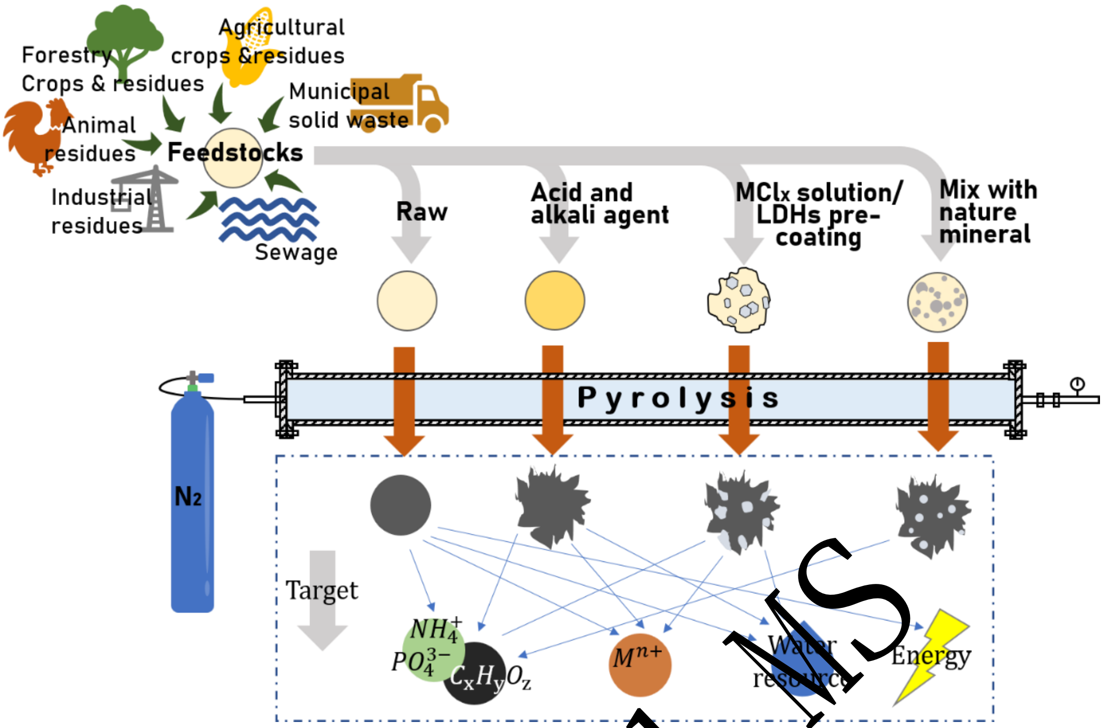

Fig. 5. Biomass feedstocks of biochar, its modification methods and recycling targets.

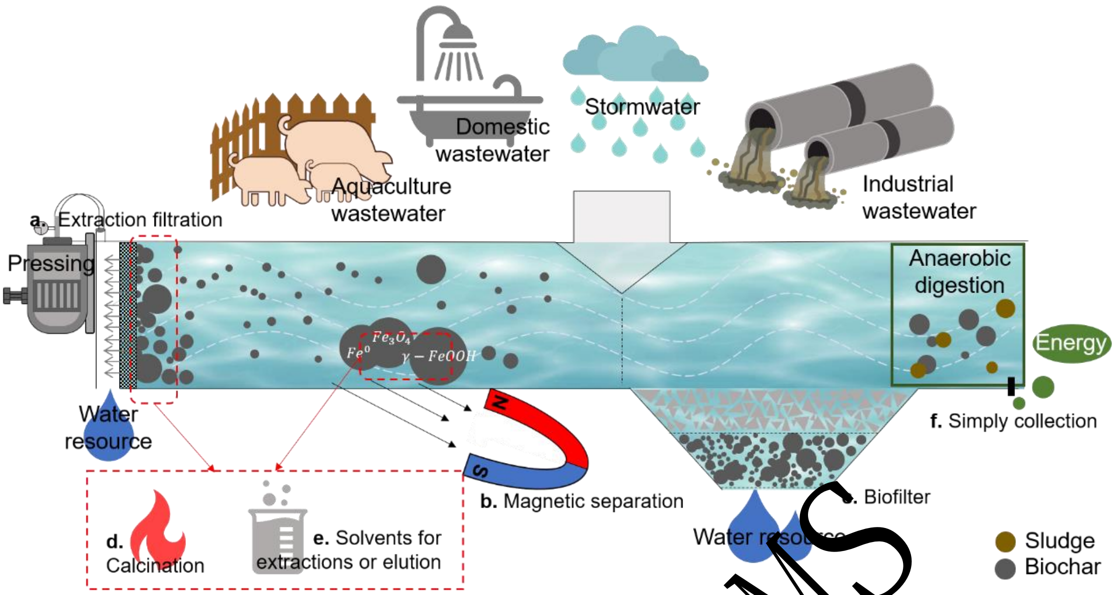

Fig. 6. Resource of wastewater, available substance recovery and separation methods. The recovery and separation methods are classified through recyclable material. Those methods are mainly used for nutrients recovery (a, b), water resource recovery (a, c), and metal recovery (d, e), respectively. The method for energy recovery (f) is simple collection due to the different characteristic of recovered substance and treatment system.

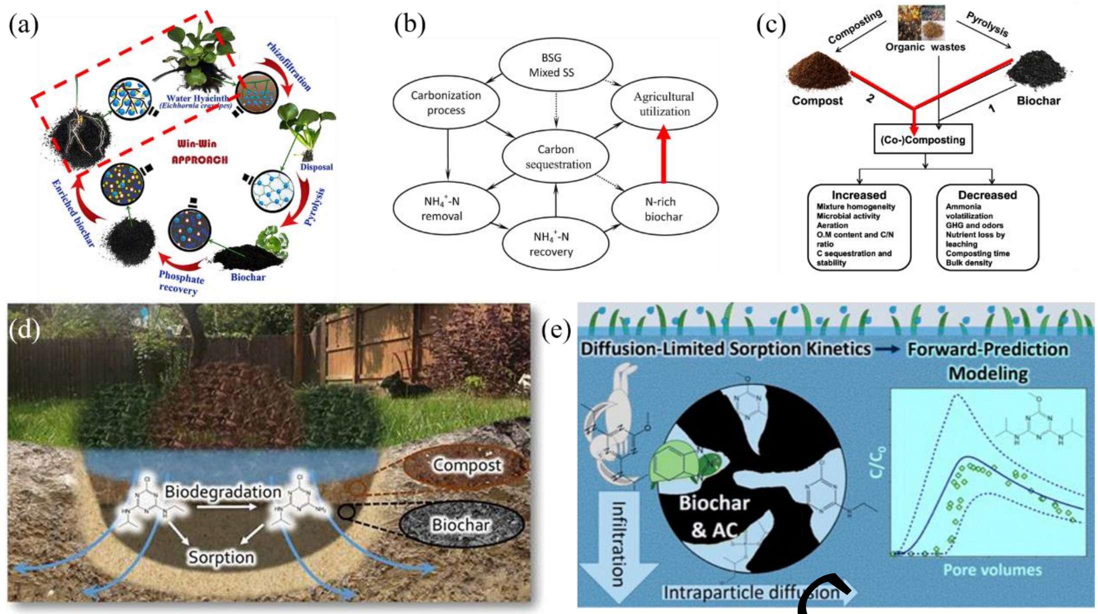

Fig. 7. Reapplication of recovered substances. (a)(b) agricultural utilization of nutrients-rich biochar [31, 39]; (c) Schematic illustration of the co-composting process for biochar and the positive effects of biochar on the composting process [113]; (d)(e) wastewater especially stormwater can be regenerated for different use with biochar [50, 53].

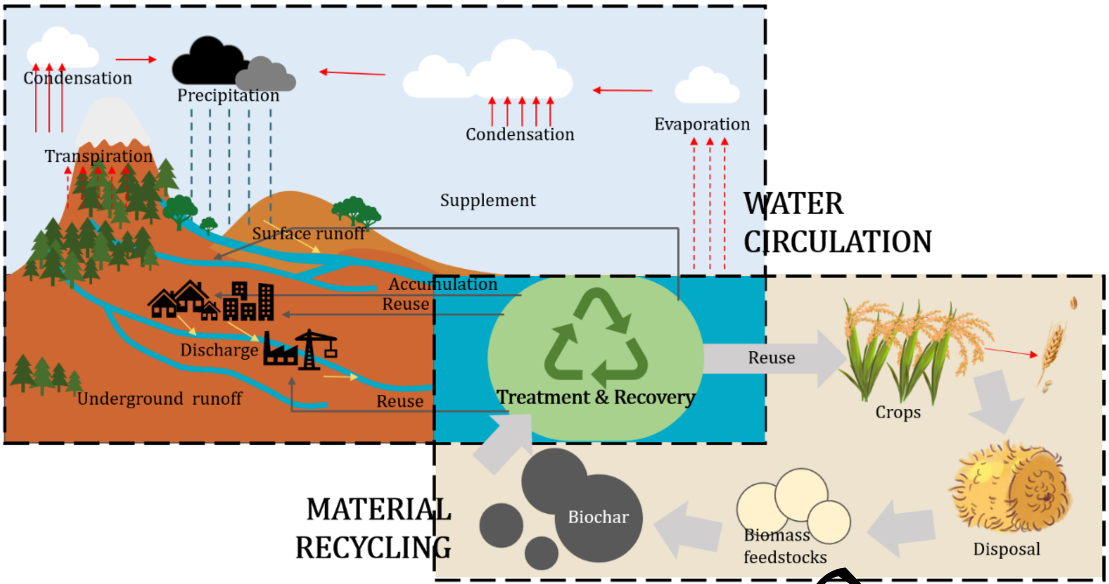

Fig. 8. The role of biochar in material recycling and water circulation.

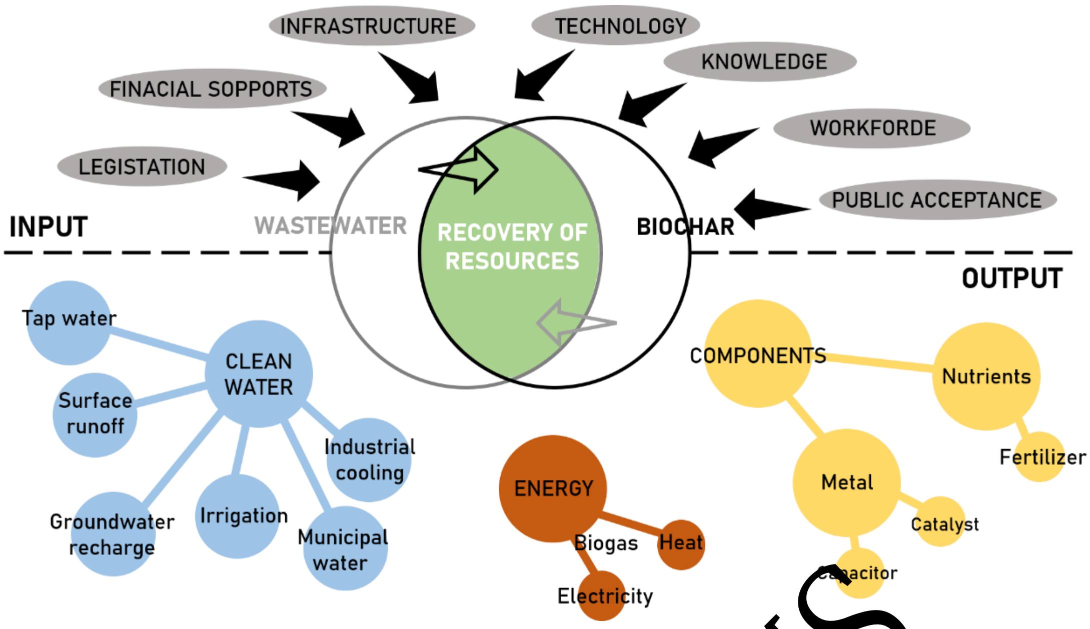

Fig. 9. Schematic view of resource recovery with biochar involvement.