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Application of the biochar in wastewater treatment

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ABSTRACT

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Water is a vital source which plays significant role in the environmental and anthropogenic processes. Wastewater treatment enables safe discharge of the water that was used for various human activities. Biochar is an emerging technology that provides wide range of application in the environmental management including wastewater treatment.

The aim of this work is to thoroughly study possible applications of the biochar in the wastewater treatment and outline its importance and advantages compared to other remediation treatments. This work also focuses on investigating current trends of the biochar application in the wastewater treatment, feasible difficulties with its implementation and possible future perspectives.

In the result it can be seen that biochar has various possible wastewater treatment applications. It is proven to be efficient in the removal of wide range of contaminants due to its possessing of the numerous sorption mechanisms and additional available physical and chemical modifications for enhanced performance. However, more research and testing are needed to ensure safe and efficient use of biochar in the wastewater treatment.

Key words: biochar, wastewater treatment, environmental management

CONTENTS

GLOSSARY or ABBREVIATIONS AND TERMS (choose one or other)

Ca	Calcium
Mg	Magnesium
K	Potassium
SSA	steady state approximation
SFG	sum frequency generation
PAH	polycyclic aromatic hydrocarbons
Fe_2O_3	iron (II) oxide, ferric oxide
Fe_3O_4	iron (III) oxide
BCs	biochar cakes
LDH	layered double hydroxide

1 INTRODUCTION

1.1 Wastewater treatment

Water is being widely used in many essential human processes, starting from general consumption and hygiene to being involved in most of the industrial manufacturing processes. However, industrial and municipal usage of water usually results with discharged water being contaminated with various chemicals that possess varying risks to environment and human health.

Due to considerable impacts of diverse water contaminants on environment, especially water sources (e.g., rivers, lakes), it is essential to provide adequate and regulated wastewater treatment and water quality control to ensure required level of safety (Liu & Liptak 2000, 13-15).

There are numerous existing wastewater treatment technologies aiming at the water purification and pollutants removal. They may be divided in three main categories: physical methods, chemical methods, and energy intensive methods.

PICTURE 1. Wastewater treatment plant ("Bolivar wastewater treatment plant." by SA Water is licensed with CC BY-NC-ND 2.0)

Physical methods of wastewater treatment are mainly working on solid-liquid separation, where filtration has a leading role. Chemical methods are based on chemical reaction of the contaminants that focuses on their removal or neutralization of their harmful effects. Energy intensive technologies are less common than other types of wastewater treatment methods but can also be used in some cases for water treatment applications, for example electrochemical techniques are widely applied for drinking water uses.

The choice of the wastewater treatment technologies is directly linked to the objectives of the wastewater treatment and additional environmental and economic factors. Some technologies can be used in combinations. Some wastewater treatment processes can include all three technology types, for example drinking water purification, which can include several types of filtration, chemical addition and reaction and energy intensive technologies.
(Cheremisinoff 2002, 1-2)

1.2 Biochar

Biochar is the carbon-rich product derived from biomass (e.g., wood, manure) through pyrolysis, thermal decomposition of organic matter with limited amount of oxygen and usually at temperatures lower 700 °C (Appendix 1). Even though the production process of the biochar is similar to charcoal and similar materials, its further application and production sources makes it different from other akin products. (Lehmann & Joseph 2009, 1)

PICTURE 2. Biochar (by Oregon Department of Forestry by SA Water is licensed with CC BY-NC-ND 2.0)

Biochar is gaining an increased interest worldwide as it provides wide application range in environmental management: greenhouse gas reduction, carbon sequestration, energy production, waste management, contaminant immobilization, soil fertilization, and water filtration. (Ok et al. 2016)

Biochar is relatively versatile material due to its complex and heterogeneous physical and chemical composition. Biochar's chemical composition relies on pyrolysis conditions (reactor type, temperature, etc.) and biomass type. Hence, biochars do not have definite outlined chemical composition.

Main component of the biochar is carbon. Biochar may also contain inorganic compounds such as Ca, Mg, K, and inorganic carbonates, depending on the biomass type. (Lehmann & Joseph 2009, 1)

1.3 Biochar and wastewater treatment

Biochars has been tested to be effective adsorbents for diverse contaminants removal due to its certain features, such as large steady state approximation (SSA), which represents overall reaction rate of a multistep reaction, nano-material content, porous structure and abundant surface functional groups (SFG) (Libretexts, 2020; Xiang et al. 2020).

Biochar has a considerably high affinity and capacity for sorbing organic compounds. Biochars' sorption affinity varies depending on the feedstock type, production temperature and production conditions (e.g., on site or in laboratory).

Certain classes of compounds are reported to be sorbed notably strongly to biochar surfaces. For polycyclic aromatic hydrocarbons (PAHs) this has been associated with certain $\pi - \pi$ interactions of the PAH molecules' aromatic rings and biochar molecules. (Lehmann & Joseph 2009, 1-9)

Biochar has proved to effectively remove following types of wastewater pollutants: heavy metals, organic contaminants, nitrogen, phosphorus (Xiang et al. 2020).

Biochar application in the wastewater treatment is increasing each year with new emerging biochar modifications and variations. Due to the versatility of the material and diverse technological production options, biochar can be applied for various remediation processes resulting in effective pollutants removal. (Xiang et al. 2020)

Due to current availability of vast studied materials about biochar and its applications, there is prominent need in summarization and analysis of this data.

2 SCOPE

The aim of this work is to thoroughly study possible applications of the biochar in the wastewater treatment and outline its importance and advantages compare to other remediation treatments. This work also focuses on investigating current trends of the biochar application in the wastewater treatment, feasible difficulties with its implementation and possible future perspectives.

3 METHODS & MATERIALS

The research is conducted by systematic investigation of the biochar and biochar applications using quantitative and qualitative research methods: content analysis, case study research, statistical research, etc. Literature review has been a main methodology for the data collection and its further analysis.

For the literature review following groups of the articles was used:

- Articles investigating the success of certain contaminants removal by biochar
- Articles investigation of overall contaminants removal by biochar derived from certain feedstock type
- Articles investigation of contaminants removal by system incorporating biochar as part of the complex wastewater treatment system (e.g., constructed wetlands)
- Articles investigating the impact of the biochar on the soil remediation resulting in the improved rate of the bioremediation of the wastewater
- Articles studying overall application of the biochar in the wastewater treatment or water remediation

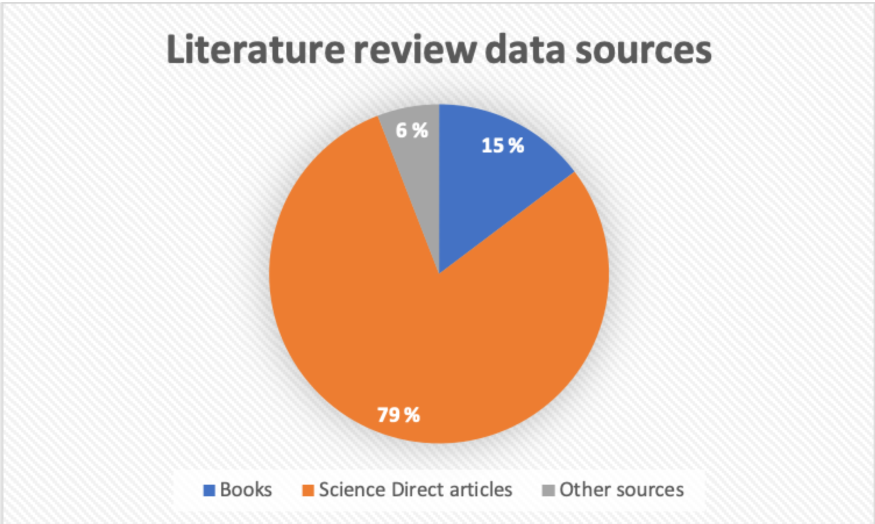
Based on the group scientific article belonged to, its relevance and novelty were analysed to decide its further use for the literature research. If article observed topic already analysed and used for the literature research, it was not furthermore implemented in the study.

Due to vast availability of the material regarding biochar, more thoroughly were studied recently published scientific articles. More profound study of recently published articles can be explained by searching tools of web sources.

In addition to the articles, which were the main information source for the research, were also analysed and studied books, describing biochar as a complex material with specific chemical, physical properties, various possible applications in environmental management and etc.

GRAPH 1. Literature research sources

Main source of the scientific articles was Science Direct due to vast availability of material regarding biochar's application in wastewater treatment (compare to other databases such as Knovel, ProQuest Ebook Central). Science Direct articles were mainly used for specific information, such as certain feedstock type or certain type of contaminant. Regarding general information about biochar, more diverse material sources were used, such as scientific books and articles from various web resources.



GRAPH 2. Research data resources

Other than data sources, various data tools were used to present and analyse information: Microsoft Word, Microsoft Excel. For data presentation were used graphs, tables, pictures and figures.

4 RESULTS

4.1 Variations of the biochar used for wastewater treatment

Biochar characteristics are directly dependent on production process variables such as temperature, maximum temperature and duration, feedstock, and atmospheric pressure inside the chamber (Bruckman & Pumpanen 2019, 427-453). However, additionally to these production variables, biochar can be chemically or physically modified in order to achieve certain case specific performance requirements.

Figure 1 presents possible biochar modifications and modifications production methods. Modified biochars have generally higher removal efficiency for particular contaminants or in certain water conditions.

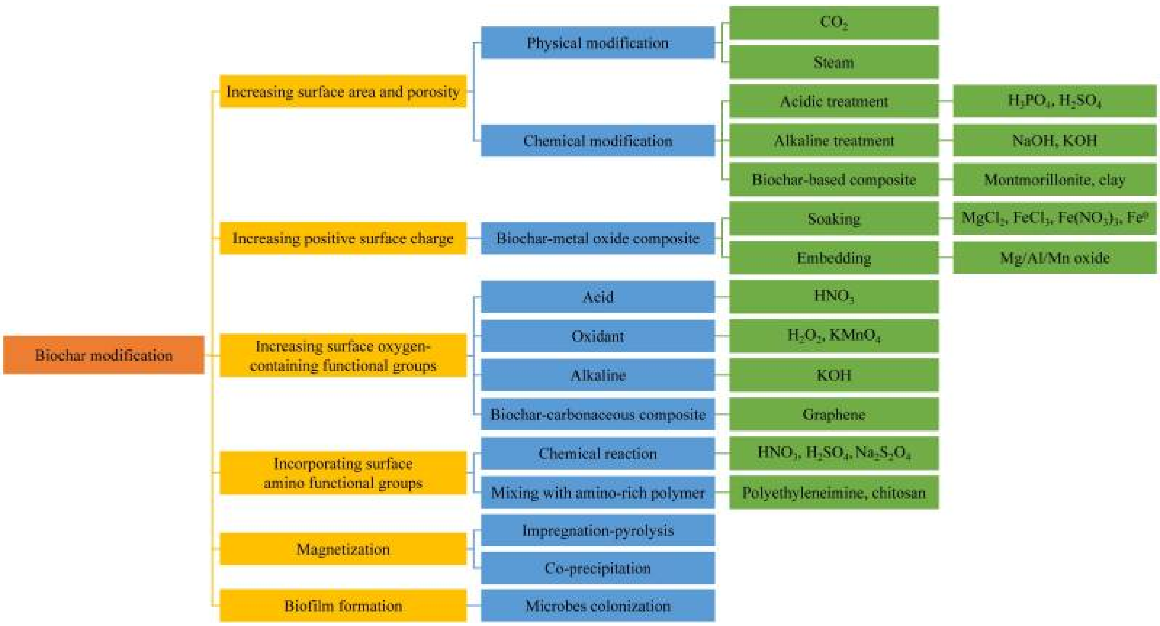


FIGURE 1. Biochar modifications (Wang et al. 2020)

Increasing surface area and porosity results in the increased sorption capacity as biochar with bigger surface area has more sorption sites. This can be achieved either by chemical or physical modifications involving various chemicals (Wang et al. 2020).

Increasing positive surface charge allows biochar to more efficiently adsorb certain chemicals, for example, oxyanions. As biochar has commonly negatively charged surface area, formation of biochar-metal oxide composite can achieve efficient removal of negatively charged oxyanions from wastewater (Wang et al. 2020).

Increasing surface oxygen-containing functional groups facilitates more sufficient chemical binding of functional groups with contaminants, thus improving the efficiency of the pollutants' removal. This modification can be achieved by various methods (e.g., forming biochar-carbonaceous composite (Wang et al. 2020).

Incorporating surface amino functional groups increases strong complexation between amino sites and wastewater contaminants, thus resulting in the enhanced sorption capacities of the biochar. This modification as well can be achieved with various methods, for example by blending biochar with chitosan (Shi, Haidong & Ren 2020).

Magnetization modification is performed in the situation when it is challenging to separate biochar from aqueous solutions. The main methods for preparing magnetic biochar are impregnation-pyrolysis and co-precipitation (Yi et al. 2020).

Biofilm formation enhances the efficiency of the contaminants removal by incorporating microbe colonization on the biochar's surface area (Wang et al. 2020).

These listed biochar modifications demonstrate how material's porosity and large surface area, as well as additional features allow to alter and improve biochar's certain performance characteristics, making it considerably versatile and functional material.

Considering studied modifications, there are many existing ways to classify biochar: for example, based on the biomass source it was produced from or based on the method biochar was produced, e.g., pyrolysis, gasification of biomass (Melas n.d.). In the Table 1 below, variations of the biochar used for wastewater treatment are presented that were differing from the commonly used form of biochar (based on their name given in the data source).

Table 1. Variations of biochar

Biochar type	Application	Source
Biochar based nano-composites. $Fe2O3$-biochar nano-composite	Used for wastewater remediation, for degradation of emerging organic pollutants	Noren & Abd-Elsalam, 2021 Chaukura et al. 2017
Steam-activated biochar	Decolorization of cationic and anionic dye-laden wastewater	Sewu et al. 2019
Biochar & magnetic Fe_3O_4 hybrids / “magnetic biochar”	Pharmaceutical removal	Liyanage et al. 2020
Photo-thermal biochar cakes (BCs)	Dye wastewater treatment	Zhai et al. 2021
Biochar based sorbents	Wastewater treatment; removal of heavy metals	Gupta et al. 2020
Biochar / layered double hydroxide (LDH) composite “Biochar/LDH composite”	Wastewater treatment; water purification	Zubair et al. 2021
Biochar filters	On-farm wastewater treatment	Perez-Mercado et al. 2019
Chitosan-modified biochar / Modified biochar/ Engineered biochar	- Organic matter removal from biotreated coking wastewater - Adsorption of emerging contaminants from wastewater - Reclaiming phosphorus from secondary treated municipal wastewater	Shi et al. 2020 Cheng et al. 2021 Zheng et al. 2019

Based on the Table 1, it can be noted that biochar has considerable number of possible alterations and modifications. From the application list, it can be concluded that each case would require its own specifically designed technique or variation. It is mainly based on pollutant type in the wastewater; however, additional factors can significantly affect the choice of the biochar treatment system (e.g., wastewater type, presence of other pollutants).

Variability of the biochar can be explained by the material's characteristics (porosity, large surface area, etc.) as well as variability and versatility of the production methods. Biomass source has direct impact on the biochar characteristics, as well as production method, production conditions and further modifications (Melas n.d.).

In the application list of Table 1, it is evident that biochar modifications are widely tested for industrial effluents with presence of hazardous substances or high concentrations of potentially dangerous chemicals. However, due to considerable number of the biochar's modifications and production variables, it is evident that the application and production of each specific formation should be carefully studied, thus notably making biochar's use in the wastewater treatment currently more challenging.

4.2 Types of pollutants in the wastewater that can be removed by biochar

Despite biochar being not widely spread technology for wastewater treatment, there are currently conducted considerable number of studies on remediation of various pollutants by biochar. However, as it was noted in the previous section, due to variability of biochar's modifications and chemical and physical properties of the biochar.

In Table 2, there are listed common pollutants that can be quite efficiently removed or reclaimed (in case of phosphorus and ammonium) by biochar and biochar modifications.

Table 2. Wastewater pollutants that can be efficiently removed by biochar

Pollutant type	Type of wastewater	Source
Heavy metals	Mainly present in industrial effluents	Gope & Saha, 2021; Zubair et al. 2021
Phosphate	Recovering phosphate from wastewater by applying engineered biochars	Shakoor et al. 2021
Phenol	Industrial wastewater	Zhao et al. 2020; Abedi & Mojiri, 2019

Ammonium, ammonia	Recovering ammonium by engineered biochars Treatment of wastewater by a constructed wetland using biochar	Abedi & Mojiri, 2019 Shakoor et al. 2021
Pharmaceuticals Tetracycline antibiotics Tylosin (antibiotic feed additive)	Removal by biochar adsorbents Removal of antibiotics from swine wastewater Removal from piggery wastewater	Liyanage et al. 2020; Zubair et al, 2021 Cheng et al. 2020 Cai et al. 2020
Inorganic anions	Industrial wastewater	Zubair et al. 2021
Organic dyes Methylene blue (dye)	Industrial wastewater	Zubair et al. 2021
COD	Removal by a biochar/zeolite constructed wetland	Abedi & Mojiri, 2019
Manganese (Mn)	Removal by a biochar/zeolite constructed wetland	Abedi & Mojiri, 2019
Bacteria	Biochar filters for on-farm treatment	Perez-Mercado et al. 2019
Naphthenic acids	Treatment of petroleum refinery wastewater	Sign et al. 2020
Phosphorus (P)	Removal of phosphorus from municipal wastewater	Zheng et al. 2019
Phenolic pollutants (phenol; 2,4 – Dinitrophenol). Ethoxylated alkylphenols and their phenolic metabolites	Removal of phenolic compounds in wastewater Removal from textile industry wastewater effluent	Thang et al. 2019 Bubba et al. 2020

It is promising that despite being able to remove common pollutants such as phosphorus, ammonium, and heavy metals, biochar is also capable to efficiently remove antibiotics (mainly form cattle farm wastewater) and organic industrial pollutants that in certain cases can be considerably toxic and dangerous.

It can be noted that biochar is capable of removing a considerable range of pollutants, both organic and non-organic. However, biochar's removal efficiency varies depending on the contaminant (Appendix 2).

As biochar is generally negatively charged, it is more challenging for the simple form of the biochar to remove negatively charged pollutants in the wastewater, for example oxyanions. Thus, certain modifications of the biochar are needed to enable efficient removal of the contaminants (Wang et al. 2019).

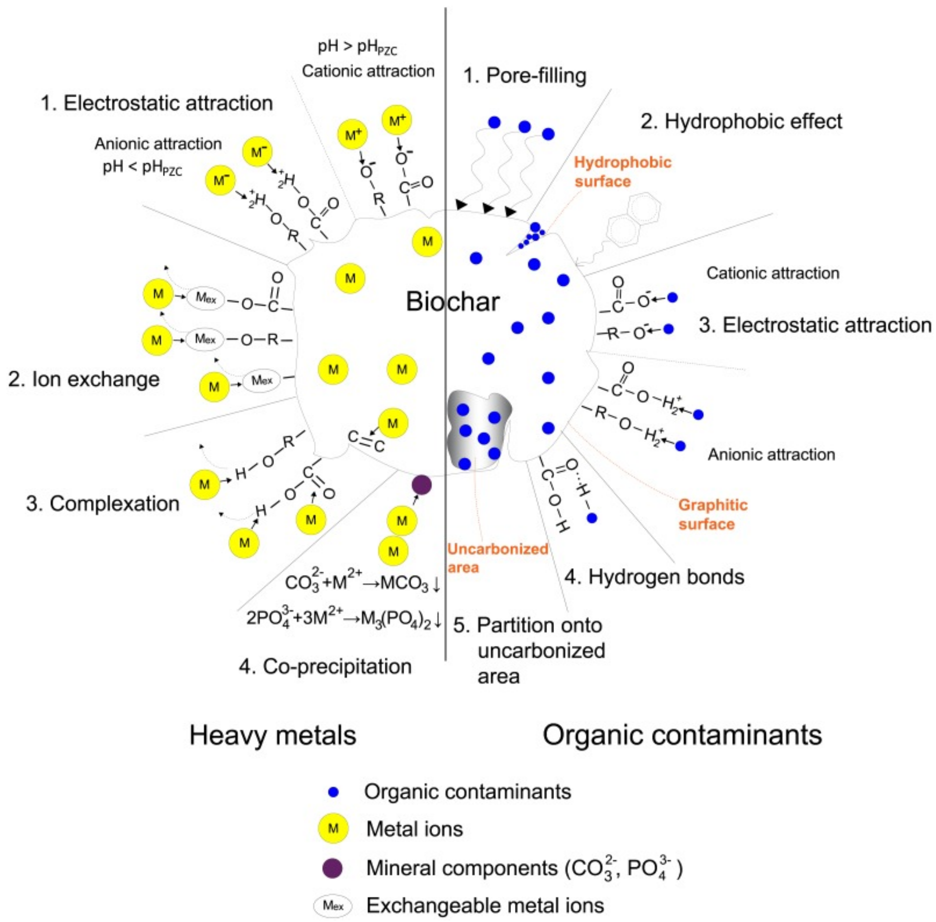
On the Picture 2, the biochar sorption mechanisms are described depending on the wastewater contaminant type. As it can be noted, contaminants in this case are divided into two groups: heavy metals and organic contaminants.

For heavy metals, dominant sorption mechanisms are electrostatic attraction, ion exchange, complexation, and co-precipitation. For organic compounds, main sorption mechanisms are pore-filling, hydrophobic effect, electrostatic attraction, hydrogen bonds, and partition onto uncarbonized area (Wang, et al).

Regarding previously studied modifications of the biochar, it is evident that in complex with these additional modifications that enable enhanced removal efficiency of the contaminants, biochar possesses considerable number of sorption (Xiang et al. 2020).

Based on the previous statements, it can be noted that the choice of the biochar, its feedstock, production temperature, possible modification and other variables are directly linked to the type of the contaminants and its chemical and physical properties.

Thus, biochar can be less efficient in the wastewater treatment if it is applied when contaminant is unknown or wastewater type (e.g., industrial or municipal) is also unknown.



PICTURE 2. Biochar sorption mechanisms of organic pollutants and heavy metals (Wang, et al)

Types of wastewater are directly linked to the contaminants present in it; thus, it is considerably important to evaluate first what was initial application of the outlet water in order for it to be treated efficiently. In the next section, types of the wastewater treated by biochar is studied more thoroughly.

4.3 Types of wastewater treated by biochar

Based on the materials used for studying variations of biochar used for wastewater treatment and types of pollutants that can be efficiently removed by biochar, following figure observing types of wastewater was generated.

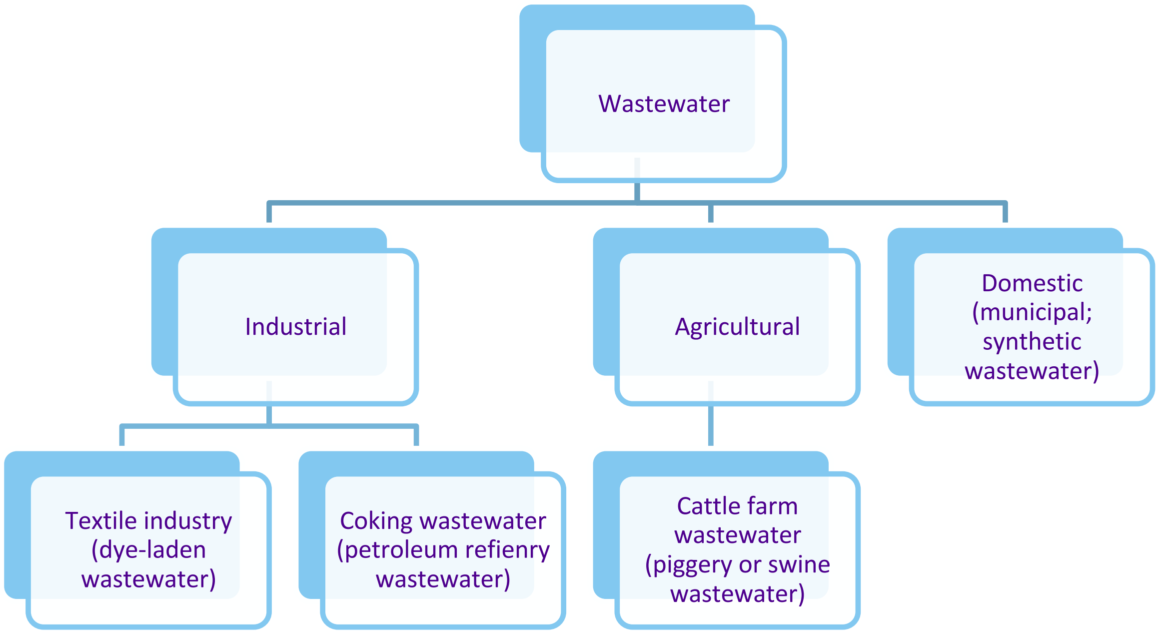


FIGURE 2. Types of wastewater treated by biochar

In the previously examined material, the biochar was mainly observed and investigated for the pollutants' removal in the industrial effluent wastewater. However, there was considerably less researches mentioning domestic or municipal wastewater as application ground of biochar for remediation (Zheng et al. 2019; Zhou et al. 2017; Ok et al. 2018).

Additionally, in some cases biochar removal efficiency was studied for specific pollutants that are commonly linked to peculiar industries, such as methylene blue dye in textile industry and naphthenic acids for petroleum industry.

Cattle farm wastewater remediation is another promising field of biochar application, as biochar can be potentially produced from animals' manure and it can effectively remove antibiotics or other potentially toxic chemicals from this type of wastewater (Thang et al. 2019).

4.4 Additional applications of biochar

Other than prevalent direct use of biochar for wastewater treatment, it can be additionally indirectly used for mainly bioremediation. In the Table 2, supplementary utilizations of biochar are presented.

Table 3. Additional applications of biochar

Application	Specification	Source
Biochar for increase of microalgal growth	Increased microalgal growth leads to increase of bioremediation of water or wastewater (incl. industrial effluents)	Sforza et al. 2020
Addition of biochar to constructed wetland. Biochar in vertical flow constructed wetland	Used for wastewater treatment.	Abedi & Mojiri. 2019 Nguyen et al. 2021; Zhou et al. 2017
Biochar as adsorbent, pH-buffer, shelter, and substrate of *Pseudomonas citronellolis*	Used for biodegradation of phenol in studied case.	Zhao et al. 2021
Combination of biochar and solar energy	Used for wastewater treatment	Zhai et al. 2021

Based on Table 2, it can be noted that indirect use of the biochar for wastewater treatment mainly includes application of the biochar for on-site treatment. Usage of biochar for bacteria or microalgal growth for the improvement or increase of bioremediation is one of the promising biochar applications that can be implemented in other scientific fields as well.

Biochar's application in the constructed wetland is an apparently the most prominent additional application of the biochar among other listed ones. Constructed wetland is a complex system that consists of many segments and is mainly aimed at treating wastewater (Parde et al. 2021).

Currently constructed wetland is not widely used as a wastewater treatment system, but it is gaining an increased interest as a considerably sustainable and self-sufficient on-site treatment with low maintenance (Zhou et al. 2017; Abedi & Mojiri, 2019)

However, it has its several substantial disadvantages (e.g., weather dependence, cost) that prevent it from being widely adopted wastewater treatment technology (Parde et al. 2021).


PICTURE 3. Construction of wetland (by Sustainable sanitation is licensed with CC BY 2.0.)

In the case of the constructed wetland biochar can play a significantly varying role: it can be incorporated as part of the constructed wetland aiming directly at the wastewater treatment or biochar can be used to enhance microalgal growth thus resulting in the improved bioremediation of the wastewater by microalgae (Abedi & Mojiri, 2019; Sforza et al. 2020).


PICTURE 4. Constructed wetland (by Sustainable sanitation is licensed with CC BY 2.0.)

Biochar's application in the constructed wetland is gaining an increased interest in the wastewater treatment bioremediation field as it has been proved to be versatile material that can be used in various fields of the environmental management.

4.5 Current and emerging trends of biochar use in wastewater

Biochar remains to be not widely used wastewater treatment technology and requires still more considerable number of tests and research works. For its further application, there are several environmental concerns and future advancement aspects that should be considered in researching. In addition to the existing environmental concerns, there are certain advised directions for future development that are outlined by Wang et al, 2020 in the Figure 3.

The first concept is the cost. Currently biochar production requires noticeable amount of preparation, including feedstock preparation, pre-treatment, pyrolysis of the feedstock and other possible additional steps, for example chemical of physical modification of the biochar, that increases overall biochar' cost.

Hence, in the future development it would be important to consider and work with this production prices as they have a direct impact on the biochar's wide applicability as a water treatment technology.

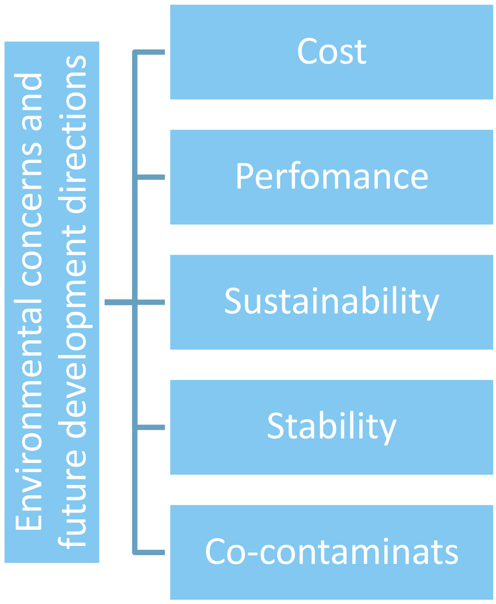


FIGURE 3. Environmental concerns and future development directions (Wang et al. 2018)

Biochar's performance is directly linked to the feedstock, production conditions and its modifications, thus it is relevant to more thoroughly research the impact of these variables on the biochar’s performance and test new possible technologies that could enhance that.

For the practical application of the biochar, its stability and stability of its modifications should be considered and evaluated. For biochar’s feedstock can be used agricultural waste products, industrial by-products, municipal wastes. However, compounds from the feedstock can significantly impact the biochar’s performance or even in some cases lead to additional contamination, for example in the case from biochar was derived from sewage sludge and contains heavy metals that during biochar’s application can flow out. Thus, the safety of the biochar’s application should be thoroughly evaluated and researched (Ok et al. 2018, 423-431).

Most of the current researches on the biochar, evaluate its removal efficiency only on certain chemical compound. However, it is evident that wastewater influent almost always is contaminated with several pollutant. Thus, there is a noticeable importance in conducting more practical test and research about biochar’s efficiency in case of several types of pollutants.

Number of demonstrated modifications of the biochar (Figure 1) shows that if biochar is still in researching phase, there is possibility to find more effective modifications to improve biochar’s performance that usually includes increased surface area, surface sorption sites or porosity.

Even if biochar’s is considered as relatively sustainable and renewable practice compare to many other technologies, it still requires conducting more test and research on its possible applications and circular use. Currently biochar’s recovery and desorption are not resolved and possesses certain challenges for its sustainable utilization (Wang et al 2018).

5 CONCLUSIONS

Biochar is an emerging technology that becomes more and more prevalent. However, there is still need in its research due to flexibility and versatility of this material and its productions methods. This research attempted to present possible applications of the biochar in wastewater treatment and summarize biochar's advantages, features, and possible difficulties with its implementation.

Currently, most of the research about biochar focuses on its application in soil remediation and soil improvement, while application of the biochar in the wastewater treatment only starts to gain more and more interest. Due to high importance of enabling sufficient water quality and presence of many variables that have an impact on the efficiency and the performance of the biochar there is a notable need in a thorough research and funding in this field.

As biochar application in the wastewater treatment research grows, there are certain existing environmental concerns as well as outlined directions that are needed to be considered during current testing and researching phase of the biochar. Safety of the biochar's application should be thoroughly evaluated due to possible risks. In addition, potential assessment and possible solutions to biochars recovery and desorption should be tested.

Most of the studied articles research and evaluate biochar's performance and removal efficiency of only one type of contaminant. However, wastewater is mainly contaminated with various pollutants. Hence, it is considerably important to research more about biochar's performance on the removal of several types of the contaminants.

To conclude, biochar's is a promising technology that is versatile and adaptable, with wide range of possible application. However, it still requires considerable research to evaluate all possible risks and concerns and enable its efficient performance in wastewater treatment.

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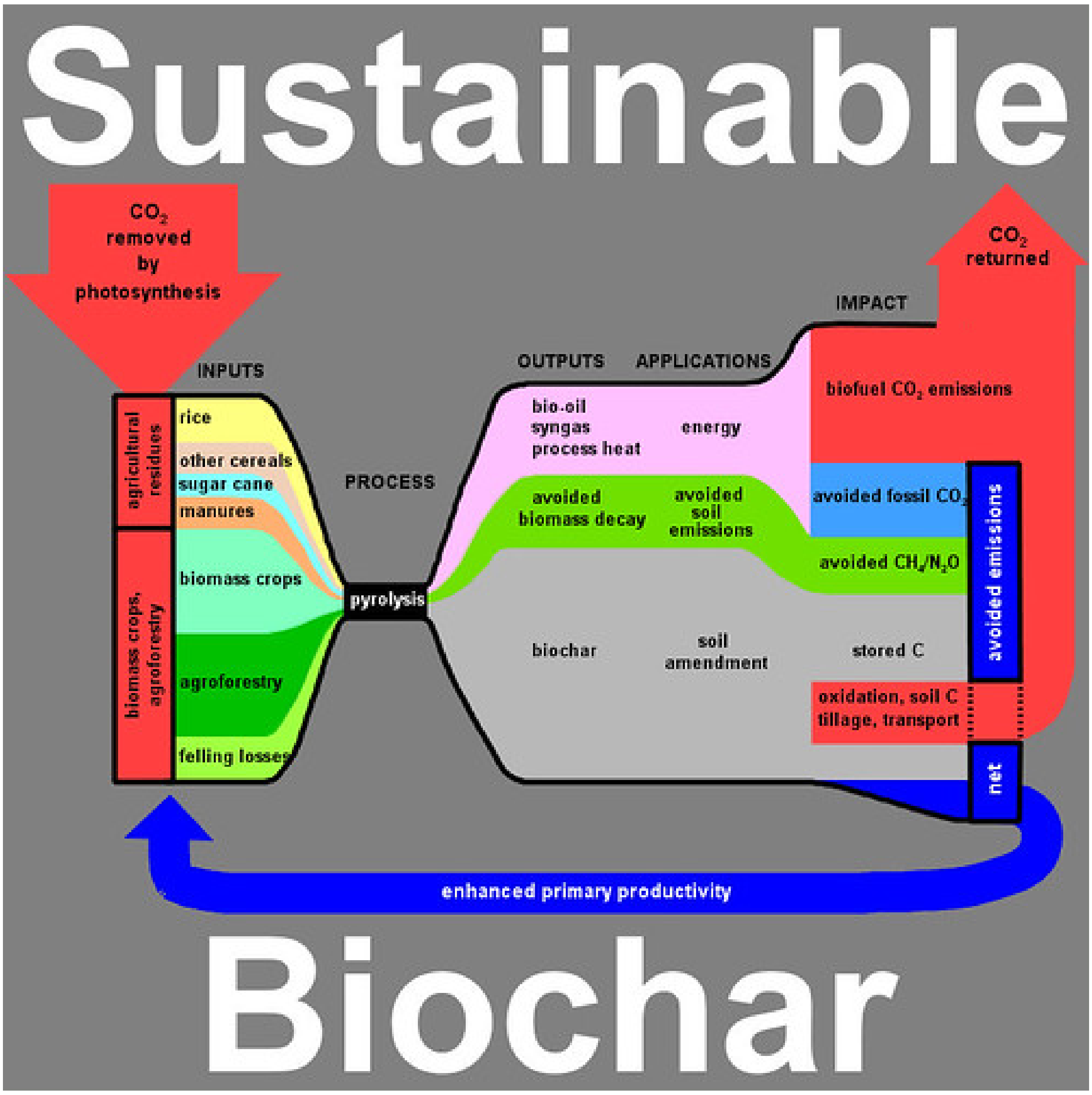
APPENDICES

Appendix 1. Sustainable production of biochar figure (Pacific Northwest National Laboratory – PNNL, CC image)



Appendix 2. Table of removal of various contaminants from water and wastewater by biochar derived from different feedstocks (Wang et al. 2018)

Table 1

Removal of various contaminants from water and wastewater by biochar derived from different feedstocks.

	Biomass feedstock	Production method	Target contaminant	Maximum removal ability	Reference
Heavy metals	Bamboo, bagasse, hickory wood, peanut hull	Pyrolysis at 600 °C then chitosan modification	Cd^{2+}, Pb^{2+}, Cu^{2+}	14.3 mg g^{-1} for Pb^{2+}	Zhou et al. (2013)
	Malt spent rootlets	Pyrolysis at 850 °C for 1 h	Hg(II)	103 mg g^{-1}	Boutsika, Karapanagioti & Manariotis (2014)
	Malt spent rootlets	Pyrolysis at 300–900 °C	Hg(II)	130 mg g^{-1} for MSR750	Manariotis, Fotopoulou & Karapanagioti (2015)
	Waste glue residue	$ZnCl_2$ modification	Cr(VI)	325.5 mg g^{-1}	Shi et al. (2020)
	Lotus stalks	Zinc borate as flame retardant, pyrolysis at 300, 350, and 400 °C	Ni(II)	61.7 mg g^{-1} for 0.5 g ZB/g LS pyrolysis at 300 °C	Liu et al. (2014)
Dyes	Bamboo cane	Phosphoric acid modification then pyrolysis at 400, 500, and 600 °C	Lanasyn Orange and Lanasyn Gray	2. 6 ×10^3 mg g^{-1} for both dyes	Pradhananga et al. (2017)
	Pecan nutshell	Pyrolysis at 800 °C for 1 h	Reactive Red 141	130 mg g^{-1}	Zazycki et al. (2018)
Phenols and PAHs	Sewage sludge	Pyrolysis at 500 °C for 1 h/microwave-assisted pyrolysis at 980 W for 12 min	Hydroquinone	1,218.3 mg g^{-1}/1,202.1 mg g^{-1}	dos Reis et al. (2016)
	Malt spent rootlets	Pyrolysis at 800 °C for 1 h	Phenanthrene	23.5 mg g^{-1}	Valili et al. (2013)
	Orange peel	Pyrolysis at 150–700 °C for 6 h	Naphthalene and 1-naphthol	80.8 mg g^{-1} for naphthalene and 186.5 mg g^{-1} for 1-naphthol	Chen & Chen (2009)
Pesticides	Maize straw and pig manure	Pyrolysis at 300, 500, and 700 °C for 4 h	Thiacloprid	About 8.1 mg g^{-1}	Zhang et al. (2018)
	Almond shell	Pyrolysis at 650 °C for 1 h with steam activation at 800 °C	Dibromochloropropane	102 mg g^{-1}	Klasson et al. (2013)
	Broiler litter	Pyrolysis at 350 and 700 °C with and without steam activation at 800 °C	Deisopropylatrazine	About 83.3 mg g^{-1} for BL700 with steam activation	Uchimiya et al. (2010)
	Maple, elm and oak woodchips and barks	Pyrolysis at 450 °C for 1 h	Atrazine and simazine	451–1,158 mg g^{-1} for atrazine and 243–1,066 mg g^{-1} for simazine	Zheng et al. (2010)
Antibiotics	Sawdust	$ZnCl_2$ and $FeCl_3$ $6H_2O$ solution doped at 100 °C then calcined at 600 °C for 2 h	Tetracycline	Above 89% after three cycles	Zhou et al. (2017)
	Potato stems and leaves	Magnetization then humic acid-coated	Fluoroquinolones	8.4 mg g^{-1} for ENR, 10.0 mg g^{-1} for NOR, and 11.5 mg g^{-1} for CIP	Zhao et al. (2019)
Indicator organisms and pathogens	Rice husk	Pyrolysis	Fecal indicator bacteria	3.9 log units of bacteria removed	Kaetzl et al. (2019)
	Hardwood	Pyrolysis	*Saccharomyces cerevisiae*	>1 log_{10} CFU of bacteria removed	Perez-Mercado et al. (2019)
	Wood chips	Pyrolysis with steam activation	*Escherichia coli*	3.62 ± 0.27 log units of bacteria removed	Mohanty et al. (2014)
Inorganic ions	Bamboo	Pyrolysis at 370 °C	NH_4^+	6.4 mM g^{-1}	Fan et al. (2019)
	Bamboo	Pyrolysis at 460 °C/immersed in clay suspension then pyrolysis at 460 °C	NO_3^-	5 mg g^{-1}/9 mg g^{-1}	Viglašová et al. (2018)
	Walnut shell and sewage sludge	Pyrolysis at 600 °C for 3 h with different ratios of the two feedstocks	PO_4^{3-}	303.5 mg g^{-1} for pure sewage sludge biochar	Yin, Liu & Ren (2019)
	Wood and rice husks	Magnetic modification by co-precipitation of Fe(II)/Fe(III) ions	PO_4^{3-}	25-28 mg g^{-1}	Ajmal et al. (2020)
	Spruce wood	Impregnated with $AlCl_3$/$FeCl_3$ solution then pyrolysis at 650 °C for 1 h	F^-	13.6 mg g^{-1}	Tchomgui-Kamga et al. (2010)