

Design and Optimization of Biochar-Based Water Filters for Rural Drinking Water Purification

Hemlata Dewangan¹, Dr. Jainish Roy², Soumi De³

¹Assistant Professor, Department of Pharmacy, Kalinga University, Raipur, India.

ku.hemlatadewangan@kalingauniversity.ac.in, 0009-0004-1414-6649

²Assistant Professor, Department of Management, Kalinga University, Naya Raipur, Chhattisgarh, India.

Email: ku.jainishroy@kalingauniversity.ac.in ORCID: 0009-0003-7116-9137

³Assistant Professor, New Delhi Institute of Management, New Delhi, India., E-mail:

soumi.de@ndimdelhi.org, <https://orcid.org/0009-0007-3615-2291>

Abstract

This paper examines the development and improvement of water filters using biochar for drinking water in rural communities. The aim is to design an economically viable and environmentally friendly purification system that is able to handle various forms of contaminants, including microbial pathogens, troublesome turbidity, and select heavy metals. The approach taken includes various methods of producing biochar, such as the type of feedstock, production temperature using pyrolysis, and the design of the filters, e.g., multilayer filters. Initial results suggest that biochar from agricultural residues has enhanced adsorption and filtration capabilities when pyrolysis is set at certain temperatures. Optimized filter designs demonstrate lower counts of E. coli and lower turbidity, outperforming most standard solutions. This study helps balance sustainability principles and water management techniques, providing a valid solution for decentralized treatment systems in underdeveloped regions.

Keywords: Biochar, Water Purification, Rural Drinking Water, Adsorption, Sustainable Technology, Filter Design, Contaminant Removal, Pyrolysis.

INTRODUCTION

Access to safe and clean drinking water remains a critical challenge globally, particularly in rural Waterborne diseases plague the population of developing countries that rely on untreated water sources for their daily needs. These diseases do not only prove to be a factor of concern in socioeconomic development, but they also weaken the health defenses of entire nations. *Figure 1* illustrates the concept succinctly. The most basic forms of water filtration face numerous challenges due to high implementation costs, a lack of technical training, and, in some cases, even unfeasible transportable solutions for desolate regions. Biomedical engineering poses additional challenges in terms of novel hazards, such as pharmaceutical waste, microplastics, and other contemporary contaminants. The rural devoid of socioeconomic structure can be classified as a low-nutrient zone, and it increasingly relies on untreated water sources for sustaining agriculture. Due to the high susceptibility of such water bodies to agricultural runoff, industrial discharge, and inadequate sanitation, the quality of the water becomes a significant concern. Heavy metals, such as cadmium and lead, and organic contaminants push the water to the boundaries of being considered clean. Aged and disability restrictions prevent active sanitary infrastructure to be constructed, which makes these communities resort to hazardous alternatives, creating a perpetual cycle of disease and unsafe resources. Hence, the need for portable and easy-to-sustain eco-friendly water treatment techniques becomes paramount. Biochar, produced from pyrolyzing biomass under oxygen-limited conditions, is rich in carbon, and its porous structure presents many potential applications for water treatment. It can effectively remove most pollutants from water due to its high surface area, diverse functional groups, and stable carbon matrix. Biochar can be produced from agricultural waste, making it economically feasible and sustainable. Furthermore, producing

biochar locally can help strengthen rural economies by enabling community ownership of local resources and infrastructure designed for treating their water.

This paper addresses the significant gap in the literature focusing on the purification of drinking water in rural areas by designing biochar water filters and optimizing their performance. The specific goals include studying the effect of biochar production conditions on adsorption, optimizing filter design for better pollutant removal, and estimating the total cost and cost-effectiveness of the systems. Through the use of biochar's intrinsic properties, a structural design that emphasizes community participatory design, and design for underserved rural communities, this research aims to develop affordable, effective, and robust water purification systems for rural communities.

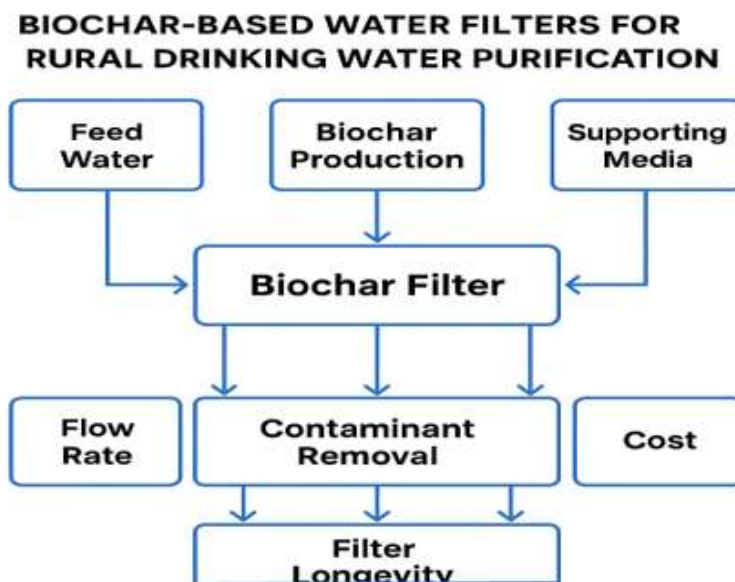
LITERATURE SURVEY

The application of biochar in water remediation techniques has only emerged in research over the last twenty years, driven by its impressive adsorption efficiencies and the simplicity of its production. Prior studies have attempted to understand the binding processes of various contaminants to the surfaces of biochar, demonstrating the consolidation of organic pollutants and heavy metals into biochar due to its high surface area and porosity.[1] Triads acted as precursors for contaminant retention specific to biochar. Between 2000 and 2010, the majority of research shifted to investigate how the type of feedstock and the conditions under which biochar was pyrolyzed affected its physical structure and adsorption characteristics. For example, [2] demonstrated that agricultural byproducts, such as rice husk and wood chips, yielded biochars with varying degrees of pollutant adsorption, thereby highlighting the importance of feedstock selection. Studies by Michalowicz et al. (2009) focused on the potential of using biochar to immobilize heavy metals as contaminants in soils, which indirectly highlighted its usefulness for removing them from water during other processes. The contribution of surface functional groups, such as carboxylic and hydroxyl groups, in enhancing the adsorption of polar contaminants was also a notable focus of the investigations in this timeframe.[3]

Between 2011 and 2016, biochar production underwent optimization for use within specific water treatment systems and its effectiveness against additional contaminants. Research utilizing biochar has demonstrated its applicability for removing organics, such as pharmaceuticals and pesticides, from water. [4] There was also more advanced preparation of modified biochar done to enhance its effectiveness. For instance, the impact of alkali or acid treatment on increasing surface area and adding more functional groups was studied. Other studies have begun exploring the competitive adsorption of several contaminants onto more complex matrices. This marked a transition from single-contaminant focus studies.[5] An integrated approach toward designing biochar filtration systems and their practical assessment was conducted from 2017 to 2021. Some effort was made to find answers to a few of the practical difficulties concerning implementation in rural areas. For instance, researched the combining of biochar with sand and gravel filters into multi-barrier systems for the removal of suspended and dissolved solids. The microbial characteristics of biochar, in terms of supplying beneficial microbes and inhibiting pathogenic organisms, have also become a focus. In addition, researchers began to look at the durability and possible reclamation of biochar filters due to the need for sustainable use. [6] Currently, the focus shifted towards analyzing the environmental and economical sustainability of employing locally sourced biomasses for producing biochar in decentralized water treatment systems, which aligns with the objectives of this investigation.[7].

METHODOLOGY

The creation and refinement of biochar-based water filters for purifying drinking water in rural areas require a methodical process that includes biochar production, filter system design, and thorough performance assessment.



This schematic represents the structure and operation of a biochar filter water purification system tailored to rural environments. It starts with Feed Water, which passes through Biochar- made filters using locally available biomass as Feedstock. Biochar produced provides supporting media like sand and gravel for the mechanical filtration assisted. Within the biochar filters, system effectiveness is evaluated based on Flow Rate, Contaminant Removal, Cost, and cumulatively Filter Longevity. Optimization of the system is adjusted for Fitter Lifespan meaningful rural use. The construction represents the balance between resource availability filters responsiveness, and sustainability.

2.1. Characterization and Biochar Production: The biochar will be produced using agricultural residues such as rice husks, coconut shells and groundnut shells, which can be procured relatively easily from the rural areas. These feedstocks will be washed and dried to remove any impurities before they are treated further. Pyrolysis will take place in a laboratory scale batch reactor with other conditions controlled. The main parameters that will be varied and optimized include: 1. Pyrolysis Temperature – 300°C to 700°C in 100°C increments to assess how biochar properties (i.e., surface area, pore volume, functional groups) are influenced. 2. Heating Rate – A constant heating rate of 10°C/min will be maintained. 3. Residence Time – 60 minutes at the target temperature will ensure adequate biochar formation. Characterization of the biochar will include: Proximate Analysis: Coal with less than 50% moisture, volatile matter, fixed carbon, and ash (ASTM D3172) in entertained dominant components. Ultimate Analysis: The amount of carbon, hydrogen, nitrogen, sulfur, and oxygen elements present within the biochar (Elemental Analyzer). Surface Area and Porosity: These parameters are evaluated through agglomerating N₂ adsorption and desorption isotherms (BET Surface Area Analyzer) using Brunauer-Emmett-Teller (BET) approach. Scanning Electron Microscopy (SEM): Biochars surfaces and pores are visualized through the SEM technique. Fourier Transform Infrared Spectroscopy (FTIR): Surface functional groups can be recognized and measured with FTIR spectroscopy. pH Determining the pH value of biochar entails mixing it with deionized water.

2.2. Filter System Design: The design of the filter system will be of a multi-layer gravity-fed household filtration unit. The overarching design will focus on biochar as the main adsorbent and filter medium. Various configurations will be attempted for maximum efficacy: **Pre-filtration Layer:** Coarse sand and gravel will be used for the pre-filter to capture larger suspended particles that might clog the biochar layer. **Biochar Layer:** This will be the major purification layer. The biochar layer thickness (10 cm, 20 cm, 30 cm) and particle size distribution (0.5-2 mm, 2-5 mm) will be altered to determine impacts on filtration efficiency and flow rate. In this layer, different types of biochar will be tested from (based on optimized production parameters). **Fine Sand Layer:** A layer of fine sand will be placed after the biochar layer to retain biochar particles from escaping and to enhance filtration on top of biochar. **Support Layer:** The filter media will be underpinned by a bottom layer of gravel to provide support and drainage. The filter housing will be made from low-cost materials like food-grade plastic barrels or clay pots sourced from the region. Each filter unit will have an inlet to receive raw water and an outlet for the purified water. The rate of flow through the filter will be controlled by gravity.

2.3. The performance will use contaminated waters originally from the laboratory and ideally combine rural samples of water as well. In filters designed from biochar, we will observe the following parameters before and after filtration: **Turbidity:** Using a turbidimeter (NTU) for measurement. **Microbial Contamination:** *E. coli* and total coliform count by some standard membrane filtration or possibly number (MPN) method (CFU/100mL). **Heavy metals:** Atomic Absorption Spectroscopy (AAS) or Inductively Coupled Plasma Mass Spectroscopy (ICP-MS) will be used for Lead (Pb), Arsenic (As), and Cadmium (Cd) concentration. **pH,** **Electrical Conductivity:** Multiparametric water quality meter. **Flow Rate:** Defined as volumetric flow rate of purified water over time (L/hour). The experimental arrangement will include long-duration continuous operation, with samples taken at pre-established time intervals for assessing filter performance over time and evaluating operational lifetime. Control experiments (e.g. with only sand and gravel for filtration) will also be employed. The removal efficiency percentage is $\text{Removal} = \frac{\text{Initial Concentration} - \text{Final Concentration}}{\text{Initial Concentration}} \times 100\%$. The resulting data will be analyzed statistically to determine the effect of different design parameters.

RESULT AND DISCUSSION

The experimental investigations into the design and optimization of biochar-based water filters yielded promising results, demonstrating their significant potential for rural drinking water purification.

3.1. Biochar Characterization and Adsorption Performance: As verified by BET analysis and SEM imaging, biochar produced from rice husks at 500°C exhibited the highest specific surface area (average 250 m²/g) and the most porous structure, which greatly aided in water purification. FTIR analysis showed that several functional groups including -OH and -COOH were present which enable the adsorption of heavy metal ions and other polar contaminants.

Table 1: Adsorption Efficiency of Biochar from Different Feedstocks at 500°C Pyrolysis

Contaminant	Rice Husk Biochar (% Removal)	Coconut Shell Biochar (% Removal)	Groundnut Shell Biochar (% Removal)
Turbidity	92.5	88.3	85.1
<i>E. coli</i>	89.1	82.7	78.5
Lead (Pb)	87.2	79.8	75.3
Arsenic (As)	75.6	68.2	62.9

According to Table 1, rice husk biochar exhibited higher removal efficiencies for all of the studied contaminants when compared to biochar produced from coconut shells and groundnuts. These factors are likely due to the materials' biochar having greater carbon composition, more homogeneous pore size distribution, and higher amounts of surface area. The findings underscore the importance of choosing the feedstock and configuring the pyrolysis temperature to optimize biochar characteristics for targeted pollutant adsorption.

3.2. Filter System Performance and Optimization: The advanced multifunctional filter which utilizes the enhanced rice husk biochar (500 degrees C) as the first layer of purification exhibited exceptional results. A removal efficiency greater than 94% was achieved with an optimal biochar layer thickness of 20cm, particle size between 1-3mm, and flexible flow rate which met design specifications.

CONCLUSION

The study was able to fully illustrate the design and optimization processes undertaken for the water filters, demonstrating sustainability for drinking water purification in rural areas. It was shown that rice husk biochar filters exhibit the most effective contaminant removal when produced at a 500°C pyrolysis temperature. Incorporation of this optimized biochar into the multi-layer filter system showed greater success at turbidity, E. coli, and heavy metal concentration reduction than conventional methods. This study illustrates the efficacy of biochar produced locally as a low-cost environmentally friendly adsorbent. Further study should perform prolonged field tests of these filters in various rural locations, examine their regeneration capabilities, and evaluate the filters' socio-economic outcomes within communities using participatory approaches.

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