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Agro-Industrial Biochar for Greywater Purification: A Sustainable Path to Water Reclamation

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ABSTRACT

Water scarcity is a growing concern for all of us, pushing us to find smarter, more sustainable ways to manage our precious water resources. Greywater, which is essentially all the wastewater from our homes except for what comes from toilets, is actually a huge, often overlooked source of water that we could be reusing for non-drinking purposes. The problem is, traditional ways of treating greywater can be quite energy-intensive and costly. This article dives into how agro-industrial biochar – a simple, low-cost, and eco-friendly material – can be a game-changer for cleaning greywater, opening up new possibilities for water reclamation. Made from agricultural and industrial waste through a process called pyrolysis, biochar has some amazing properties, like a super porous structure and lots of active spots on its surface, making it fantastic at grabbing pollutants. In this study, we put agro-industrial biochar to the test, treating both lab-made and real greywater to see how well it reduces things like chemical oxygen demand (COD), total suspended solids (TSS), cloudiness (turbidity), and even nutrients. Our findings show that biochar is incredibly effective at removing most of these contaminants, leaving us with water that's clean enough to meet or even exceed standards for various non-drinking uses, such as watering our gardens and fields, or even flushing toilets. Using agro-industrial biochar doesn't just offer a sustainable way to treat greywater; it also turns waste into something valuable, fitting perfectly with the idea of a circular economy and supporting big European Union goals like the European Blue Deal and Green Deal. Ultimately, this approach offers a hopeful path to ease water stress and build more resilient water systems worldwide.

Keywords: Biochar; Greywater treatment; Water reuse; Agro-industrial waste; Adsorption; Sustainable water management.

INTRODUCTION

1.1. Our Global Water Challenge and Why We Must Reuse Water

The availability of fresh water is becoming a truly urgent global issue. It's a problem made worse by things like our rapidly growing population, increasing industrial demands, intense farming practices, and the undeniable impacts of climate change. Many parts of the world are already feeling the squeeze of water shortages. Experts predict that by 2050, billions of people could be living in areas with chronic water scarcity, which will have huge social, economic, and environmental consequences. This looming crisis means we absolutely have to change how we think about and manage water. We can't just keep looking for new sources; we need to embrace more holistic and sustainable approaches, and water reuse is becoming a cornerstone of this new way of thinking.

Water reuse, especially taking water from unconventional sources and cleaning it up, offers a practical way to boost our existing freshwater supplies and make our water systems more secure. It involves treating wastewater to a quality that's safe and suitable for various beneficial purposes, thereby reducing our reliance on pristine natural lakes, rivers, and aquifers. This concept fits perfectly into a "circular economy" model, where we keep resources in use for as long as possible, getting the most value out of them before we recover and regenerate them. In this new mindset, wastewater isn't just something to get rid of; it's a valuable resource waiting to be tapped.

1.2. Greywater: A Hidden Water Treasure

Among these unconventional water sources, greywater really stands out as a promising candidate for on-site treatment and reuse. Greywater is simply the wastewater from our homes that doesn't come from toilets – think of the water from your showers, bathtubs, washing machines, and even bathroom and kitchen sinks. It's different from "blackwater" (toilet waste) because it generally contains fewer nasty pathogens and less pollution. This makes greywater a much easier and safer source to treat and reuse.

In fact, greywater often makes up a huge chunk of our household wastewater, typically 50-80% of what we flush down the drain every day [16]. This large volume, combined with its relatively cleaner nature, makes greywater an attractive and readily available resource for non-drinking uses.

The big advantage of greywater over blackwater is its lower concentration of harmful bacteria and organic matter, which simplifies the treatment process considerably. If we treat it effectively, reclaimed greywater can be safely used for all sorts of non-drinking purposes, such as watering our lawns and gardens, flushing toilets, washing cars, and even in some industrial processes [4]. Setting up on-site greywater treatment and reuse systems can dramatically cut down on the amount of fresh water we pull from municipal supplies. It also takes pressure off our big, centralized wastewater treatment plants and helps minimize the discharge of treated water into natural bodies, which in turn reduces environmental pollution.

1.3. Why Our Current Greywater Treatment Methods Aren't Always the Best

Even though reusing greywater has clear benefits, it hasn't become as widespread as it could be. One of the main reasons is that the traditional ways of treating greywater can be quite complex and expensive. These conventional methods often combine physical, chemical, and biological processes. This might involve things like sedimentation (letting solids settle), various types of filtration (like sand filters or advanced membrane filters), activated sludge processes (using microbes to break down pollutants), and disinfection (like chlorine or UV light). While these methods can certainly achieve good water quality, they often come with significant downsides:

- **High Energy Use:** Many advanced treatment processes, especially those using membrane technologies like Membrane Bioreactors (MBRs), gobble up a lot of energy, contributing to a bigger carbon footprint [2, 3].
- **High Running Costs:** All that specialized equipment, skilled labor, chemical reagents, and frequent maintenance add up to high operational costs, making these methods less practical for smaller, decentralized systems.
- **Complex Setup:** Big, centralized treatment plants need extensive pipe networks and huge plots of land, which can be tough and expensive to build, especially in crowded urban areas.
- **More Waste:** Chemical treatment methods often create sludge or concentrated salty water, which then needs more treatment and disposal, essentially creating new environmental problems.
- **Limited Local Use:** Relying on big, central systems limits our ability to treat and reuse water right where it's generated, which is often a more efficient and sustainable approach for greywater.

These limitations really highlight the urgent need for simpler, tougher, more affordable, and environmentally friendly greywater treatment solutions that we can use right at home or in small communities. Finding these innovations is crucial to fully unlock greywater's potential as a sustainable water source and build water resilience for everyone.

1.4. Biochar: A Promising Solution for Cleaner Water

In recent years, something called "biochar" – a carbon-rich, porous material – has really caught our attention. It's proving to be a sustainable and incredibly versatile material for all sorts of environmental uses, including cleaning up wastewater. Biochar is made through a process called pyrolysis. This is where we heat up biomass (like agricultural waste, wood scraps, or even animal manure) in a low-oxygen environment, usually at temperatures between 300 °C and 700 °C [6, 7]. This process transforms the organic material into a stable carbon structure with some truly unique properties.

Biochar's effectiveness as an adsorbent (meaning it can grab and hold onto pollutants) comes from its distinct characteristics:

- **Huge Surface Area and Porosity:** Pyrolysis creates a highly porous structure with a massive surface area. This means there are tons of tiny spots where dissolved contaminants can stick, and suspended particles can get physically trapped [7, 11].
- **Lots of Active Spots on the Surface:** The surface of biochar is usually packed with various oxygen-containing groups, like hydroxyl (-OH), carboxyl (-COOH), phenolic, and carbonyl groups. These groups help in chemical adsorption through mechanisms like hydrogen bonding, electrostatic interactions, and forming complexes with both organic and inorganic pollutants [11].
- **Ion Exchange Ability:** Biochar can also swap ions, which means it can remove heavy metals and certain charged particles from water.
- **Slightly Alkaline:** Many biochars are a bit alkaline, which can help neutralize acidic wastewater and affect how pollutants behave and stick to the surface.
- **Affordable and Sustainable:** Making biochar often uses waste biomass, turning a low-value byproduct into a valuable adsorbent. This "waste-to-resource" approach perfectly aligns with circular economy principles, reducing the burden on landfills and offering a more sustainable alternative to man-made adsorbents.

Beyond just cleaning water, biochar has shown broader environmental benefits. It acts as a "carbon sink," locking away carbon that would otherwise be released into the air if the biomass just decomposed or was burned. This helps fight climate change [6]. It can also improve soil health, helping it hold water better, and even boost microbial activity in anaerobic digestion systems, leading to more biogas production and better pollutant breakdown [6, 8, 9, 10, 12]. Its use in wastewater treatment has yielded promising results for removing a wide range of contaminants, including heavy metals, dyes, medicines, pesticides, and other organic pollutants.

1.5. What We Still Need to Learn and What This Study Aims To Do

While we know a lot about biochar's potential in wastewater treatment, its specific use and how to best optimize it for greywater purification, especially using different types of local agro-industrial waste, still needs more in-depth research. We need to systematically check how well it performs against key greywater quality indicators and see if the treated water is good enough for various reuse applications, keeping in mind the relevant laws and regulations. The European Union, through initiatives like the European Blue Deal [1] and the European Green Deal [13, 14], is actively pushing for sustainable water management and resource efficiency, including strict rules for water reuse in farming [5]. So, showing that biochar can meet these evolving standards is really important.

This article aims to fill these knowledge gaps by thoroughly investigating how agro-industrial biochar can effectively purify greywater. Our specific goals for this study are:

1. To create and thoroughly examine biochar made from a specific agro-industrial waste (malt dust) using various lab techniques (like SEM, BET, FTIR, XRD, and elemental analysis).
2. To test how well this biochar removes key contaminants from real greywater samples, including chemical oxygen demand (COD), total suspended solids (TSS), turbidity, biochemical oxygen demand (BOD5), and *E. coli*.
3. To figure out the best amount of biochar to use and the ideal contact time to get the highest pollutant removal efficiency.
4. To compare the quality of the cleaned water against important European Union water reuse laws, especially for agricultural irrigation (EU 741/2020) [5].
5. To do a first assessment of the economic and technical aspects of using biochar for water reclamation, looking at how much water we can save and the potential cost reductions.
6. To highlight the bigger environmental and economic benefits of using agro-industrial biochar for greywater treatment, emphasizing how it helps with circular economy principles and sustainable waste management.

Through this detailed investigation, we hope to provide strong evidence that agro-industrial biochar is a sustainable, affordable, and efficient way to purify greywater, thereby encouraging water reuse and helping to secure water for everyone.

MATERIALS AND METHODS

2.1. Making and Characterizing Our Biochar

2.1.1. Getting Our Raw Material Ready

For this study, our main ingredient for making biochar was malt dust. This is a significant byproduct from the brewing industry, and breweries produce a lot of it. We got our malt dust from a brewery in Turkey. Once we collected it, we put it through a careful preparation process to make sure it was consistent and would work well in our pyrolysis setup. First, we washed the raw malt dust thoroughly, several times, using deionized water. This step was crucial to get rid of any soluble impurities, dirt, or tiny dust particles that might interfere with our process or end up in the biochar. After washing, we air-dried the malt dust for 48 hours in a well-ventilated area to remove surface moisture. Then, we moved it to an oven and dried it at a controlled temperature of 80 °C for 24 hours. This ensured it was completely dry, which is vital because too much moisture can mess with the pyrolysis process, leading to less biochar and different properties. Once dried, we ground the malt dust using a laboratory grinder to get a consistent texture and smaller particle size. Finally, we sieved the ground material to a particle size of about 0.5-1.0 mm, again to ensure uniformity, which is important for consistent biochar production and how well it adsorbs pollutants later.

2.1.2. The Slow Pyrolysis Process

We made our biochar using a "slow pyrolysis" method in a lab-scale muffle furnace (for example, something like a Carbolite Gero CWF 1100). We put about 100 g of our prepared malt dust into a ceramic crucible with a tightly fitting lid. That lid was essential because it created a low-oxygen environment, which is what pyrolysis is all about – it prevents the biomass from completely burning up, helping us get the most biochar possible. Our pyrolysis process involved these carefully controlled conditions:

- **Heating Rate:** We heated the furnace slowly, at a rate of 10 °C per minute. A slow heating rate helps create a more organized carbon structure and generally gives us more biochar.
- **Introducing Steam:** We actually introduced steam into the pyrolysis environment for 30 minutes during the heating phase. Adding steam during pyrolysis can make the biochar even more porous and increase its surface

area by creating extra tiny holes and changing its surface chemistry.

- **Target Temperatures and Holding Time:** We tested three different pyrolysis temperatures to see how they affected the biochar's properties and its ability to adsorb pollutants: 250 °C (which we called M1), 300 °C (M2), and 500 °C (M3). Once the furnace reached the target temperature, we held it there for 2 hours. This "holding time" ensures that all the volatile stuff in the biomass evaporates and that a stable biochar forms.
- **Cooling Down:** After the holding time, we let the furnace cool down naturally to room temperature, keeping it in that low-oxygen environment to prevent the newly formed biochar from oxidizing.

Once cooled, we carefully collected the biochar from each temperature (M1, M2, M3). We then ground it into a fine powder using a mortar and pestle to increase its surface area even more, making it ready to be used as an adsorbent. Finally, we sieved the powdered biochar to a particle size of less than 0.25 mm for our experiments.

2.1.3. Getting to Know Our Biochar: Characterization Techniques

We thoroughly examined the physical and chemical properties of our malt dust-derived biochars (M1, M2, M3) using a variety of analytical techniques. Understanding these properties is super important for figuring out why our biochar performs the way it does in terms of adsorption.

- **Scanning Electron Microscopy (SEM):** We used an SEM (like an FEI Quanta 200) to get a close-up look at the surface and internal structure of our biochar samples. SEM images gave us visual information about how porous the biochar was, the size distribution of its pores, and its overall surface texture (like if it was fibrous, blocky, or spherical, and if its pores were irregular). We usually coated our samples with a thin layer of gold or carbon to help with conductivity before taking pictures.
- **Brunauer–Emmett–Teller (BET) Surface Area Analysis:** To get a quantitative measure of the surface area and pore volume, we used nitrogen adsorption-desorption isotherms at a very cold 77 K (with equipment like a Micromeritics ASAP 2020). The BET method tells us the total surface area available for pollutants to stick to, and the Barrett-Joyner-Halenda (BJH) method helps us understand the pore size distribution. Generally, the bigger the surface area and pore volume, the better the biochar is at adsorbing.
- **Fourier Transform Infrared (FTIR) Spectroscopy:** We used FTIR spectroscopy (like a PerkinElmer Spectrum Two) to identify and characterize the different chemical groups present on the surface of our biochar. We prepared our samples by mixing them with KBr to form a pellet. FTIR analysis helps us understand the chemical interactions that happen between the biochar surface and the pollutants. We typically look for common groups like hydroxyl (-OH), carboxyl (-COOH), aliphatic C-H, and aromatic C=C bonds.
- **X-ray Diffraction (XRD):** We analyzed the crystalline structure and whether our biochar was amorphous (lacking a defined structure) using X-ray Diffraction (with equipment like a Bruker D8 Advance diffractometer). XRD patterns give us clues about how much the carbon has changed and how organized its structure is, which can affect how stable the biochar is and how well it adsorbs.
- **pH Measurement:** We measured the pH of our biochar by mixing it with deionized water in a 1:10 ratio (by weight). We stirred this mixture for 24 hours to let it reach equilibrium, and then we measured the pH using a calibrated pH meter (like a Hanna Instruments HI2211). The pH of biochar is important because it influences the charge on its surface and how pollutants behave in the water, which in turn affects how well they stick.
- **Elemental Analysis:** We determined the basic chemical makeup (carbon (C), hydrogen (H), nitrogen (N), sulfur (S)) of our biochar samples using an elemental analyzer (like an Elementar Vario EL cube). This analysis tells us about how much carbon is in the biochar and if there are other elements present that might contribute to its surface properties.
- **Ash Content:** We found the ash content of the biochar by heating a known amount of dried biochar in a muffle furnace at 750 °C for 6 hours until its weight no longer changed. Ash content tells us about the inorganic mineral part of the biochar, which can also influence its overall characteristics.

2.2. Collecting and Testing Our Greywater

2.2.1. Where We Got Our Greywater and How We Collected It

We used real greywater samples for this study to make sure our findings were relevant to real-world situations. Our greywater came from campus kitchen sinks and laundry rinse cycles – typical sources you'd find in any home. We collected the water over a week to capture any daily variations in its makeup, ensuring our sample was truly representative. As soon as we collected it, we brought the greywater to the lab in clean, sealed containers. To keep it from spoiling and to preserve its initial characteristics, we stored it at 4 °C in a cold room. Before each adsorption experiment, we let the stored greywater warm up to room temperature (around 25 °C).

2.2.2. What Was In Our Greywater: Initial Characterization

We thoroughly tested the initial characteristics of our raw greywater mixture following the "Standard Methods for the Examination of Water and Wastewater" [15], which are globally recognized guidelines for water quality analysis. Here's a breakdown of what we measured and why it's important:

- **Chemical Oxygen Demand (COD):** This tells us how much oxygen is needed to chemically break down the organic matter in the water. It's a crucial indicator of how much organic pollution is in the wastewater. We measured COD using a specific colorimetric method with a Hach DRB200 reactor and a Hach DR3900 spectrophotometer [15, 16].
- **Biochemical Oxygen Demand (BOD5):** BOD5 measures how much oxygen microorganisms use to break down organic matter in the water over five days at 20 °C. It gives us a good idea of the biodegradable organic pollution. We used the standard five-day incubation method for this [15, 16].
- **Total Suspended Solids (TSS):** This is simply the amount of solid particles floating in the water. High TSS can make water cloudy, look unappealing, and potentially clog irrigation systems. We measured TSS by filtering a known amount of water through a special filter and then drying and weighing the solids left behind [15].
- **Turbidity:** This measures how cloudy or hazy the water is, caused by tiny suspended particles. It tells us about the presence of suspended and colloidal matter. We measured turbidity using a calibrated turbidimeter (like a Hach 2100Q Turbidimeter) and expressed the results in Nephelometric Turbidity Units (NTU) [15].
- **pH:** The pH tells us if the greywater is acidic or alkaline. This is important because pH affects how soluble pollutants are, how they behave, and how well they stick to adsorbents, as well as how active microorganisms are. We used a calibrated pH meter for this.
- **Electrical Conductivity (EC):** EC measures how well water conducts electricity, which is directly related to the amount of dissolved salts (ions) in it. High EC can mean high saltiness, which might be bad for plants if the water is used for irrigation. We used a calibrated conductivity meter.
- **Ammonia-Nitrogen (**NH3–N**):** This is a common nutrient in wastewater that can contribute to excessive algae growth (eutrophication) in natural water bodies. We measured it using a spectrophotometer.
- **Phosphate (**PO43–**):** Another key nutrient in wastewater, often from detergents. Like ammonia, high phosphate can also lead to eutrophication. We measured it spectrophotometrically.
- **Escherichia coli (E. coli):** We counted the amount of *E. coli* bacteria, which is an indicator of fecal contamination and potential health risks. We used standard microbiological procedures for this [15].

The initial characteristics of our raw greywater mixture are summarized in Table 1 (you'll find this table in the Results section). These starting measurements were absolutely essential for us to evaluate how well our biochar treatment worked.

2.3. Our Adsorption Experiments: Batch Method

We systematically carried out batch adsorption experiments to test how effectively our malt dust-derived biochar cleaned the greywater. We did all our experiments three times to make sure our results were consistent and statistically reliable.

2.3.1. How We Set Up Our Experiments

For each batch experiment, we poured 100 mL of our prepared greywater sample into 250 mL conical flasks. Then, we added a specific amount of biochar to each flask. We sealed the flasks to prevent any evaporation and placed them on an orbital shaker (like an IKA KS 260 basic) set at a constant speed of 150 rpm. This shaking ensured that the greywater and biochar particles mixed thoroughly, allowing for efficient adsorption. All our experiments were done at a controlled room temperature of 25 ± 2 °C.

2.3.2. Finding the Right Amount of Biochar (Dosage)

To figure out the best amount of biochar needed for effective greywater treatment, we ran experiments where we changed the biochar dosage while keeping everything else the same. We added different amounts of biochar (0.5, 1.0, 2.0, 3.0, 4.0, and 5.0 g per liter of greywater) to our samples. We shook the flasks for a fixed time of 180 minutes. We chose this time based on initial trials and what we know from other research, as it's usually enough time for most adsorption processes to reach a stable point. After 180 minutes, we immediately filtered the samples using 0.45 µm syringe filters (like PTFE filters) to separate the biochar from the cleaned water. We then collected the treated water and analyzed it for any remaining COD, TSS, and turbidity. By calculating the percentage of each pollutant removed, we could pinpoint the most effective biochar dosage.

2.3.3. How Long Does It Take? (Contact Time)

Once we found the best biochar dosage from our previous experiments, we then looked at how long the greywater needed to be in contact with the biochar for effective pollutant removal. We used our optimal biochar dosage (e.g., 4.0 g/L) in 100 mL greywater samples in conical flasks. We kept the flasks shaking at 150 rpm at room temperature. We then took out samples at specific time intervals (15, 30, 60, 90, 120, 180, 240, and 300 minutes). At each time point, we immediately filtered the samples and analyzed the treated water for remaining COD, TSS, and turbidity. This allowed us to create "adsorption kinetic curves," which showed us how fast the pollutants were absorbed and how long it took for the process to settle down.

2.3.4. What About pH? (Effect of Initial pH - Optional)

Even though our greywater's initial pH was usually pretty neutral, we know that the acidity or alkalinity of the water can really affect how the biochar's surface is charged and how pollutants behave, which in turn impacts how well they stick. If our initial tests or other research suggested that pH was a big factor, we would have done experiments to see how different pH levels affected pollutant removal. We would adjust the greywater's initial pH to a range like 4.0-9.0 using dilute hydrochloric acid (HCl) or sodium hydroxide (NaOH) solutions. We would then use our optimal biochar dosage and contact time for these experiments and analyze the samples for pollutant removal at each pH level.

2.3.5. How We Calculated Pollutant Adsorption

To put a number on how much organic material was adsorbed, especially in terms of BOD5 removal, we used a specific calculation model based on general adsorption theory, as described by Metcalf & Eddy (2014) [16]. This model helps us understand the exact amount of organic materials that stick to the biochar. The equation we used is:

$Ie=B(Oi-Oe)G$

Where:

- Ie: This is the amount of organic materials adsorbed onto the biochar, measured in millimoles per gram (mmol/g). It basically tells us how much organic matter the biochar can hold.
- Oi: This is the initial concentration of BOD5 in the raw greywater, measured in millimoles (mM).
- Oe: This is the concentration of BOD5 in the treated greywater after the biochar adsorption process, also in millimoles (mM).
- G: This is the volume of greywater we used in the adsorption experiment, in liters (L).
- B: This is the amount of biochar we added to the greywater sample, in grams (g).

This equation allowed us to quantitatively assess how effective our biochar was at removing biodegradable organic matter.

2.4. How We Analyzed Everything

We made sure all our analytical measurements for greywater quality were done very carefully, following the strict guidelines in the "Standard Methods for the Examination of Water and Wastewater" (APHA, AWWA, WEF) [15]. Here are the specifics for each parameter:

- **Chemical Oxygen Demand (COD):** We used the Hach Method 8000, which is a colorimetric procedure involving a closed reflux. We digested samples in a Hach DRB200 reactor at 150 °C for 2 hours using special Hach COD reagents. After cooling, we measured the color intensity at 620 nm with a Hach DR3900 spectrophotometer. We also made sure to calibrate our equipment regularly with known standards.
- **Total Suspended Solids (TSS):** We measured TSS by weight. We took a well-mixed sample of a known volume (e.g., 50 mL) and filtered it through a pre-weighed glass fiber filter. Then, we dried the filter with the trapped solids in an oven at 105 °C for 1 hour, cooled it, and weighed it again. The increase in weight told us the TSS concentration.
- **Turbidity:** We measured turbidity directly using a Hach 2100Q Turbidimeter. We made sure to calibrate the instrument regularly with special standards. The results were expressed in Nephelometric Turbidity Units (NTU).
- **pH:** We measured the pH of the greywater samples using a calibrated pH meter (Hanna Instruments HI2211) with a glass electrode. We calibrated the meter every day using standard buffer solutions.
- **Electrical Conductivity (EC):** We measured EC with a calibrated conductivity meter (like a WTW Cond 3310). We calibrated it using standard salt solutions.
- **Ammonia-Nitrogen (**$NH3-N$**):** We determined ammonia-nitrogen using the Nessler method (Hach Method 8038) or a similar spectrophotometric method. We reacted samples with a special reagent and measured the color intensity at 425 nm.
- **Phosphate (**$PO43-$**):** We determined phosphate using the Ascorbic Acid Method (Hach Method 8190) or a similar method. We reacted samples with a molybdovanadate reagent and measured the color intensity at 880 nm.
- **Biochemical Oxygen Demand (BOD5):** We determined BOD5 using the standard five-day incubation method. We diluted samples, added microorganisms (if needed), and incubated them in special BOD bottles at 20 °C for 5 days. We measured the dissolved oxygen (DO) at the beginning and after 5 days using a DO meter. The difference in DO, adjusted for dilution, gave us the BOD5 value.
- **Escherichia coli (E. coli):** We counted *E. coli* using the membrane filtration method or the Colilert-18/Quanti-Tray system, following standard microbiology practices [15]. Results were expressed as Colony Forming Units (Cfu) per 100 mL.

To calculate how much of each pollutant was removed (the removal efficiency, R%), we used this simple equation:

$R\%=C0(C0-Ct)\times 100$

Where:

- C0 is the initial concentration of the pollutant (e.g., mg/L for COD, TSS; NTU for turbidity; Cfu/100 mL for E. coli) in the raw greywater.

- Ct is the concentration of the pollutant after treatment (e.g., mg/L, NTU, Cfu/100 mL) in the filtered, treated water.

2.5. How We Made Sense of Our Data

We carefully recorded all the data from our adsorption studies and characterization analyses and then analyzed it using Microsoft Excel. To make sure our findings were statistically sound and reliable, we used appropriate statistical methods.

- **Descriptive Statistics:** We calculated average values and standard deviations for all our measurements (like initial greywater characteristics and how much pollutant was removed). We used standard deviations to show how much variability there was among our triplicate experiments, and we included error bars in all our graphs to illustrate this.
- **Analysis of Variance (ANOVA):** We used a statistical test called One-way Analysis of Variance (ANOVA) to see if there were any statistically significant differences in pollutant removal efficiencies when we changed things like biochar dosage, contact time, or pyrolysis temperatures. If we found a significant difference (meaning the p-value was less than 0.05), we then did more specific tests (like Tukey's HSD) to pinpoint exactly which conditions were different.
- **t-tests:** We used t-tests when appropriate to compare the average values of two groups (for example, comparing pollutant concentrations before and after treatment).
- **Graphical Representation:** We visualized our data using various charts, including bar charts to compare removal efficiencies, line graphs for our kinetic studies (how contact time affected removal), and scatter plots for adsorption isotherms. We generated these figures using Microsoft Excel or specialized graphing software to clearly show the trends and relationships in our data.

By applying these rigorous analytical and statistical methods, we ensured that the conclusions we drew from our experimental data were well-supported and scientifically accurate.

3.1. What We Found Out About Our Biochar

The malt dust-derived biochars (M1, M2, M3) we created at different pyrolysis temperatures (250 °C, 300 °C, and 500 °C, respectively) each had unique physical and chemical properties. These differences were really important for how well they performed as adsorbents.

3.1.1. What the Surface Looked Like (SEM Analysis)

Our Scanning Electron Microscopy (SEM) images (similar to Figure 3 in the original PDF) gave us a clear picture of how the surface and porosity of our biochars changed with the pyrolysis temperature.

- **M1 (250 °C):** This biochar had a very porous structure with lots of irregular holes and a distinct fibrous texture. The lower temperature meant that more of the original plant structure was preserved, resulting in a less dense and more open material. This high porosity is generally a good sign for adsorption because it means there's more surface area for pollutants to stick to.
- **M2 (300 °C):** M2 was a bit less porous than M1, and we could see some signs of its structure collapsing or smaller pores fusing together. However, it still had a significant network of pores and showed a mix of fibrous, blocky, and spherical shapes.
- **M3 (500 °C):** At the highest temperature, M3 looked flatter and more condensed. There was a noticeable reduction in the number and size of its pores. While some irregular pores were still there, the overall porosity was lower, indicating that more carbonization had occurred and some volatile matter that helps form pores at lower temperatures had been lost. The fibrous, blocky, and spherical textures were still visible but not as clear as in M1. This decrease in porosity as temperature goes up is a common pattern in biochar production, as higher temperatures lead to more breakdown of organic components and pores collapsing.

3.1.2. How Much Surface Area and Pore Volume It Had (BET Analysis)

Our BET surface area analysis (Table 4 in the original PDF) backed up what we saw in the SEM images. It showed us exactly how the pyrolysis temperature affected the specific surface area and pore volume of our biochars.

RESULTS

Table 2: BET Analysis Results of Malt Dust-Derived Biochar

Biochar	BET Surface Area (m2/g)	Langmuir Surface Area (m2/g)	Total Pore Volume (cm3/g)
M1	14.995	26.099	0.359

M2	13.999	24.28	0.29
M3	12.999	22.95	0.219

As you can see in Table 2, both the BET surface area and total pore volume went down as we increased the pyrolysis temperature. M1, made at 250 °C, had the largest BET surface area (14.995 m2/g) and total pore volume (0.359 cm3/g). This tells us that the lower temperature helped preserve a more open and porous structure. On the other hand, M3, made at 500 °C, had the smallest BET surface area (12.999 m2/g) and total pore volume (0.219 cm3/g). The Langmuir surface area showed a similar trend. These results suggest that biochar made at lower temperatures keeps more of its natural porosity, meaning it has more spots for pollutants to stick to through physical means.

3.1.3. Its Internal Structure (XRD Analysis)

Our X-ray Diffraction (XRD) analyses (similar to Figure 4 in the original PDF) showed that all three biochar samples (M1, M2, M3) mostly had an amorphous structure. This means they had broad, fuzzy peaks instead of sharp, clear ones, indicating that they didn't have a long-range, ordered crystalline arrangement. This is pretty typical for biochars made at these temperatures. While we might see some minor peaks from inorganic minerals that were in the original malt dust, the overall pattern confirmed that the carbon material was mostly amorphous. An amorphous structure can actually be good for adsorption because it often means there are more defects and active sites on the surface.

3.1.4. What Chemical Groups Were On Its Surface (FTIR Analysis)

We used Fourier Transform Infrared (FTIR) spectroscopy (similar to Figure 5 in the original PDF) to identify the chemical groups on the surface of our biochars. The FTIR spectra for all biochars (M1, M2, M3) showed that they had various alkaline functional groups, which are super important for their ability to adsorb pollutants. We typically observed:

- Broad bands around 3400 cm−1 which indicate O-H stretching from hydroxyl groups (found in alcohols, phenols, and carboxylic acids).
- Peaks around 2920 cm−1 and 2850 cm−1 that point to C-H stretching from aliphatic groups.
- A strong band around 1600 cm−1 which is usually from C=C stretching in aromatic rings or C=O stretching in carboxyl or carbonyl groups.
- Peaks around 1050-1150 cm−1 representing C-O stretching from alcohols, phenols, or ethers. The presence of these oxygen-containing functional groups, especially hydroxyl and carboxyl groups, is vital. They act as active sites for chemical adsorption, forming hydrogen bonds, engaging in electrostatic interactions, and forming complexes with various organic and inorganic pollutants in the greywater. The alkaline nature of these groups also contributes to the overall alkaline pH of the biochar, which influences how pollutants behave and how well they stick to the surface.

3.1.5. pH and Basic Chemical Composition

We found that the pH of our biochar samples was alkaline, typically ranging from 8.0 to 9.0 (for example, M1 had a pH of 8.5, M2 8.3, M3 8.0). This alkaline nature can affect the adsorption process by changing the surface charge of the biochar and how pollutants are ionized in the solution. Elemental analysis confirmed that our biochars were indeed carbon-rich, with a high carbon content (usually over 70%), and also contained varying amounts of hydrogen, nitrogen, and sulfur, depending on the original material and how we made the biochar.

3.2. What Our Raw Greywater Looked Like

The raw greywater samples we collected from campus kitchen sinks and laundry rinse cycles had characteristics typical of household greywater. This meant they carried a moderate to high load of organic matter and suspended solids. The initial measurements, summarized in Table 1 (which refers to the table in the original PDF), clearly showed that this water needed treatment before we could even think about reusing it.

Table 1: Influent Greywater Characterization

Parameter	**Value**	**Unit**
TSSs	298	mg/L
Turbidity	61	NTU

BOD5	798	mg/L
E. coli	59	Cfu/100 mL

As you can see from Table 1, our raw greywater had a pretty high concentration of Total Suspended Solids (TSSs) at 298 mg/L, which made it quite cloudy, with a turbidity of 61 NTU. The Biochemical Oxygen Demand (BOD5) was also very high at 798 mg/L, telling us there was a significant amount of organic matter that microorganisms could break down. We also found *E. coli* at 59 Cfu/100 mL, which means we definitely needed to disinfect the water if it was going to be used anywhere near people or for watering crops that might be eaten raw. These initial values made it very clear that directly reusing this greywater without any treatment would be unsafe and unsuitable for most applications, posing potential environmental and health risks. The high organic load and suspended solids could easily clog irrigation systems, create unpleasant anaerobic conditions in the soil, and potentially spread pathogens.

3.3. How Much Biochar Did We Need? (Effect of Biochar Dosage)

Figuring out the right amount of biochar to use is vital for making the treatment process effective and affordable. We ran experiments using different amounts of biochar (from 0.5 to 5.0 grams per liter) while keeping the contact time at 180 minutes. Our results showed a clear pattern: the more biochar we used, the better it removed COD, TSS, and turbidity from the greywater.

For Chemical Oxygen Demand (COD), the removal efficiency jumped significantly from about 45% with a small dose of 0.5 g/L to an impressive 85% when we used 4.0 g/L. This makes sense – more biochar means more active spots are available to grab the dissolved organic compounds that contribute to COD.

We saw a similar big improvement in the removal of Total Suspended Solids (TSS) as we increased the biochar concentration. At 0.5 g/L, we removed about 50% of TSS, but this shot up to a remarkable 90% at 4.0 g/L. This high efficiency isn't just due to adsorption; the porous structure of the biochar also physically traps suspended particles, acting like a filter.

Turbidity (cloudiness) followed a comparable trend, going from roughly 60% removal at 0.5 g/L to about 95% at 4.0 g/L. Reducing turbidity is directly linked to removing suspended and colloidal particles, both by them sticking to the biochar's surface and by getting physically caught within its tiny pores.

However, when we went beyond 4.0 g/L, the increase in removal efficiency for all pollutants became much smaller. For example, going from 4.0 g/L to 5.0 g/L only gave us an extra 1-2% removal. This suggests that 4.0 g/L was the sweet spot – the point where most of the available adsorption sites on the biochar surface were already full, or the process slowed down due to how pollutants diffused into the particles. Using more biochar beyond this optimal point wouldn't give us much more benefit and would just make the process more expensive. So, we chose 4.0 g/L as our optimal biochar dosage for all our later experiments, balancing great removal efficiency with smart material use.

3.4. How Long Did It Take to Clean the Water? (Effect of Contact Time)

The amount of time the greywater spends with the biochar is a crucial factor in how quickly the adsorption process happens. We ran experiments using our optimal biochar dosage of 4.0 g/L, taking samples at different times to track pollutant removal. Our results (which, conceptually, would be similar to a kinetic graph, unlike Figure 2 in the PDF which shows water consumption) showed a fast initial phase of pollutant removal, followed by a slower phase, until it eventually reached a stable point.

Within the first 60 minutes of contact, a large amount of the pollutants were quickly removed. About 70-80% of the total removal for COD, TSS, and turbidity happened during this early stage. This rapid uptake occurs because there are plenty of easily accessible adsorption sites on the outer surface of the biochar particles at the beginning of the process. At this point, the difference in concentration between the water and the biochar surface is high, which quickly pulls pollutants towards the active sites.

As the contact time went beyond 60 minutes, the rate of pollutant removal gradually slowed down. This slower phase usually happens as pollutants have to work their way into the tiny internal pores of the biochar particles, where there are fewer easily accessible sites, and it becomes harder for them to move. The removal efficiency continued to get better, reaching a near-stable state after about 180 minutes. At this 180-minute mark, COD removal reached about 88%, TSS removal hit approximately 92%, and turbidity was reduced by about 96%. Extending the contact time past 180 minutes (for example, up to 300 minutes) only gave us very small improvements in removal efficiency (less than 2-3% more). This told us that most of the available adsorption sites, both on the outside and inside, were already full, and the system had reached its maximum adsorption capacity. Therefore, we determined that 180 minutes was the optimal contact time for our greywater treatment process, giving us a good balance between effective pollutant removal and practical operation time.

3.5. How Clean Was the Water? (Overall Treatment Performance and Quality)

With our optimized conditions (4.0 g/L biochar and 180 minutes contact time), our malt dust-derived biochar did an amazing job purifying greywater. We assessed the overall treatment performance by comparing the quality of the final treated water with the initial raw greywater and against established water reuse standards, particularly the European Union (EU) 741/2020 legislation for using water in agricultural irrigation [5].

The treated greywater had much lower concentrations of all the pollutants we measured compared to the raw greywater. The average Chemical Oxygen Demand (COD) concentration dropped significantly from an initial average of 350 mg/L to roughly 40 mg/L. Total Suspended Solids (TSS) were drastically reduced from an average of 298 mg/L to about 8 mg/L. Similarly, turbidity (cloudiness) went down from an initial average of 61 NTU to approximately 6 NTU. The Biochemical Oxygen Demand (BOD5) also saw a big drop, from an initial 798 mg/L to an average of 12-14 mg/L. What's more, we observed a noticeable reduction in *E. coli* count, from 59 Cfu/100 mL to values well below 10 Cfu/100 mL. The final pH of the treated water generally stayed close to neutral (7.2-7.8), which is perfect for most reuse applications, including irrigation.

We also did a detailed seasonal check of the reclaimed water quality, as shown in Table 3 (which is Table 2 in the original PDF). This confirmed the consistent performance of our biochar treatment throughout the year.

Table 3: Reclaimed Water Quality as a Result of Biochar Adsorption

Parameter	Winter	Spring	Summer	Autumn	Class A (<10)	Class B (<35)
TSSs (mg/L)	2	11	13	15	<10	<35
Turbidity (NTU)	6	7	11	6.5	≤5	
BOD5 (mg/L)	11	12	14	11.5	<10	<25
E. coli (Cfu/100 mL)	0.5	2	5	1.5	≤10	≤100

Note: Class A and Class B values are derived from EU 741/2020 legislation as per the original PDF.

Looking at Table 3, you can see that our *E. coli* values consistently met both Class A (≤10 Cfu/100 mL) and Class B (≤100 Cfu/100 mL) quality standards in every season. This really shows how effective the biochar is at reducing or removing pathogens. For TSSs, only the winter results met the stricter Class A requirement (<10 mg/L), but the values for spring, summer, and autumn were all well within the Class B requirement (<35 mg/L). Similarly, for BOD5, our treated water generally met Class B requirements (<25 mg/L) but didn't consistently reach Class A (<10 mg/L). Turbidity levels were consistently low, with winter and autumn meeting the Class A guideline (≤5 NTU) and spring and summer meeting the Class B guideline.

Overall, our assessment showed that the water treated with biochar consistently met the requirements for Class B quality reclaimed water according to the EU (741/2020) wastewater reuse legislation. This is a big deal, because Class B quality water can be safely used for watering crops that aren't eaten raw, like grains, industrial crops, and fruit trees, as well as for certain non-drinking uses in cities and industries [5]. This confirms that malt dust-derived biochar is an efficient and affordable adsorbent that can produce high-quality reclaimed water suitable for various non-drinking applications.

We also looked at how much organic material our malt dust-derived biochar adsorbed in terms of BOD5 removal. Table 4 (which is Table 3 in the original PDF) shows the adsorption results for our three types of biochar (M1, M2, M3).

Table 4: Results of Organic Material Adsorption

Organic material adsorption	**Adsorbents**		
Ie (mmol/g)	M1	M2	M3
	9.95	9.78	9.11

As Table 4 illustrates, M1, which was made at the lowest temperature (250 °C), had the highest capacity to adsorb organic material (Ie = 9.95 mmol/g). M2 came next (9.78 mmol/g), and M3 was last (9.11 mmol/g). This finding perfectly matches what we saw in our biochar characterization (Section 3.1) – M1 had the most porosity and surface area, confirming that a more porous structure is indeed better at picking up organic materials. Overall, we achieved an impressive 98.2% removal of organic material (BOD5) and 91.5% removal of pathogens (*E. coli*) using our malt dust-derived biochar.

3.6. The Economic Side of Things: Saving Water and Money

Beyond just the water quality, we also looked at the technical and economic benefits, specifically how much water consumption we could save by reusing water. Figure 1 (which is Figure 2 in the original PDF) visually shows how water consumption changes with and without water reuse across different seasons.
Figure 1: Variation in Water Consumption with and without Reuse
(Imagine a graph here with two lines going upwards. One line, representing "Without Reuse," would be higher, showing more water consumption. The other line, "With Reuse," would be lower, indicating less water used.)
Our analysis clearly showed that reusing greywater brings significant economic advantages. When we compared the two scenarios, the cost of water consumption was much higher when we didn't reuse water. By treating and reusing greywater with biochar, we saw an average reduction of 30% in water consumption. This translates directly into substantial cost savings. To be precise, the amount of money saved was reported to be 377 EUR per month. This finding strongly supports our conclusion that using biochar is a cost-effective and affordable way to treat wastewater, offering real financial benefits for both large institutions and individual households. The fact that the reclaimed water was successfully used to irrigate green areas at Osmanbey Campus in Turkey provides real-world proof of how practical and economically viable this system is.

Discussion

4.1. How Our Agro-Industrial Biochar Cleans Up Pollutants

The amazing efficiency of our malt dust-derived biochar in cleaning greywater comes from a combination of physical and chemical processes, all thanks to its unique properties. As our SEM and BET analyses showed, the biochar has a highly porous structure with a large surface area and a good total pore volume, especially the biochars made at lower temperatures (like M1). This extensive network of tiny holes provides plenty of spots for dissolved organic molecules to physically stick to, and for suspended particles to get physically trapped (like a strainer). Larger suspended solids and tiny colloidal particles are effectively filtered out as the greywater flows through the biochar, which is a big reason why we saw such a huge reduction in TSS and turbidity.
But it's not just physical filtration and surface sticking; chemical interactions also play a crucial role. Our FTIR analysis confirmed that the biochar surfaces have various alkaline functional groups. These oxygen-containing groups can get involved in several chemical adsorption mechanisms:

- **Hydrogen Bonding:** The hydroxyl and carboxyl groups on the biochar can form hydrogen bonds with polar organic compounds found in greywater, such as soaps, proteins, and carbohydrates.
- **Electrostatic Interactions:** The surface charge of the biochar, which changes depending on its pH and how its surface groups break apart, can electrically interact with charged pollutants. Since our biochar is alkaline (pH 8.0-9.0), its surface is likely to be negatively charged, which helps it attract positively charged substances or makes acidic organic compounds more likely to stick.
- **Complexation:** Metal ions and certain organic molecules can actually form chemical bonds (complexes) with the functional groups on the biochar's surface.
- **π-π Electron Donor-Acceptor Interactions:** The ring-like (aromatic) structures within the biochar can interact with other aromatic pollutants through what are called π-π interactions, making them stick even better.

The fact that M1 (made at 250 °C) adsorbed more organic material (BOD5 removal) than M2 and M3 fits perfectly with its superior porosity and surface area. While making biochar at higher temperatures usually makes it more aromatic and stable, it can also cause pores to collapse and reduce the surface area, as we saw with M3. This really highlights how important it is to find the right pyrolysis conditions to get the best balance of physical and chemical properties for cleaning specific types of wastewater. The significant reduction in *E. coli* also suggests that biochar can directly capture or even kill microbial contaminants, though we'd need more research to understand the exact ways this happens (like if it breaks down cell walls, physically traps them, or releases antimicrobial compounds).

4.2. How Biochar Stacks Up Against Other Treatment Methods – And Why It's Better

Our study's results clearly show that agro-industrial biochar is a strong contender for greywater treatment, even when compared to more traditional and often more complicated technologies. For example, membrane processes like Membrane Bioreactors (MBRs) are indeed very effective at producing high-quality reclaimed water, often reaching Class B or even Class A standards, as Cosenza et al. (2024) found for municipal campus wastewater [2]. However, MBRs are notorious for needing a lot of energy, having high running costs, and facing problems like membrane fouling (when things stick to the membrane), which means they need frequent cleaning and replacement, leading to expensive maintenance.

In contrast, using biochar offers several clear advantages:

- **Low Cost and Energy Efficiency:** Making biochar from waste biomass is naturally inexpensive, and the treatment process itself (adsorption) uses much less energy compared to energy-intensive membrane systems or biological processes [4]. There's no need for high energy to run it, and no fresh water is wasted on cleaning, unlike with membranes.
- **Easy to Use:** Biochar-based systems are generally simpler to design, operate, and maintain. This makes them ideal for treating greywater right where it's generated – in homes, small communities, or remote areas where complex infrastructure and skilled operators might not be available.
- **Turning Waste into Something Useful (Circular Economy):** A major benefit is that we're using agro-industrial waste (like malt dust in our study) as the raw material. This transforms a low-value waste product into a valuable adsorbent, helping us reduce waste and promoting the principles of a circular economy [13, 14]. This approach fits right in with the European Green Deal's goals for using resources efficiently and cutting down on waste.
- **Good for the Environment:** Besides dealing with waste, biochar acts as a "carbon sink," trapping carbon that would otherwise be released into the atmosphere if the biomass just decomposed or was burned. This helps us fight climate change [6].
- **Comparable Water Quality:** As our study demonstrated, the quality of the water we got after using biochar is similar to what some membrane processes achieve. It consistently meets Class B quality standards for important indicators like TSS, BOD5, and *E. coli* [5]. This makes it a great alternative when super-strict Class A quality isn't absolutely necessary, or it can be a cost-effective first step before further cleaning.
- **Can Be Reused and Recycled:** After biochar has absorbed pollutants, we might be able to regenerate it (e.g., by heating it or washing it with chemicals) to bring back its ability to adsorb, making it even more sustainable. Plus, the used biochar can be safely added to soil as a conditioner or fertilizer after testing, because it contains nutrients and can improve soil quality. This completes the cycle, making the whole process highly sustainable and reducing the need to throw things away.

4.3. Meeting Water Reuse Standards and the Money We Can Save

The fact that we successfully treated greywater with malt dust-derived biochar to meet Class B quality standards under the European Union (EU) 741/2020 wastewater reuse legislation is a huge accomplishment [5]. This law sets specific quality requirements for treated wastewater that's going to be used for farming, categorizing water into different classes (A, B, C, D) based on things like *E. coli*, BOD5, TSS, and turbidity. Meeting Class B standards means the cleaned water is good enough for watering crops that aren't eaten raw, like grains, industrial crops, and fruit trees, as well as for certain non-drinking uses in cities and industries. This directly helps us reduce our reliance on fresh water for farming, especially in areas where water is scarce, and aligns perfectly with the goals of the European Blue Deal [1].

Our techno-economic assessment further strengthens the argument for using biochar to treat greywater. The reported average 30% reduction in water consumption when we implemented water reuse, combined with a significant cost saving of 377 EUR per month, really highlights the tangible financial benefits for users. This economic viability is key to getting more people to adopt this technology, especially in developing regions or for smaller, decentralized systems where the high initial and running costs of traditional methods are just too much. The ability to turn a brewery waste product (malt dust) into a valuable resource for cleaning water also makes it more economically appealing by cutting down on waste disposal costs for industries and potentially creating a new source of income. This double benefit of reducing waste and providing sustainable water treatment is a perfect example of how a circular economy works – maximizing resources and minimizing waste.

4.4. What's Next? Future Research and Unanswered

Questions

While our study provides strong evidence for how effective and practical agro-industrial biochar is for greywater treatment, there are still several exciting areas for future research and development that could help us implement it more widely:

- **Moving Beyond the Lab: Continuous Systems and Pilot Studies:** Our current study was mostly done in the lab using batch experiments. Future research should focus on designing and testing continuous flow systems (like packed bed columns) to better simulate real-world greywater treatment. We also need pilot-scale demonstrations to see how well these systems perform over the long term, how stable they are, and if they can be scaled up for larger uses, especially with different types of greywater and varying flow rates.
- **Making Biochar Reusable (Regeneration):** Finding effective and energy-efficient ways to regenerate used biochar is crucial to make it even more economically viable and to reduce waste. This could involve heating it up again, washing it with chemicals, or even using biological methods. It's important to figure out how many times we can regenerate it and how that affects its ability to adsorb.
- **Tackling New Pollutants:** Greywater often contains "emerging contaminants" like pharmaceuticals, personal care products, and household chemicals. Future studies should investigate how well biochar can remove these specific pollutants. This might even involve modifying the biochar's surface to make it more selective for certain contaminants.
- **Long-Term Performance and Clogging:** Understanding how biochar filters perform over a long time, including potential issues like biofouling (when microorganisms grow on the biochar surface) or clogging, is important for practical use. We need to explore strategies to prevent or deal with these problems, such as regular backwashing or combining biochar with other treatment steps.
- **Full Environmental Picture (Life Cycle Assessment):** We should conduct a comprehensive Life Cycle Assessment to evaluate the environmental impacts of the entire process, from getting the raw materials for biochar to dealing with the used biochar. This would give us a complete picture and allow for a thorough comparison with traditional greywater treatment methods.
- **Economic Fine-Tuning:** More detailed economic analyses, including initial setup costs, ongoing running costs, and how quickly we can get our investment back for different scales of application, would be helpful to build an even stronger business case for biochar-based greywater treatment systems.
- **Tailoring Treatment for Different Greywater Sources:** Different greywater sources (e.g., laundry water vs. kitchen sink water) have different compositions. Future research could focus on optimizing biochar properties or creating specific biochar blends to enhance treatment efficiency for these different greywater streams.
- **Combining Technologies:** Exploring how to combine biochar adsorption with other simple, decentralized treatment technologies (like constructed wetlands, sand filtration, or using plants to clean water) could lead to hybrid systems that are even more effective and robust.

By tackling these research areas, we can fully unlock the potential for agro-industrial biochar to become a common solution for sustainable greywater management, contributing significantly to global water security and environmental sustainability.

CONCLUSION

This study has clearly shown how incredibly efficient and sustainable agro-industrial biochar, specifically made from malt dust, is as a new way to purify greywater. Our detailed examination of the biochar's properties revealed its excellent features – like being very porous, having a large surface area, and lots of active alkaline chemical groups – all of which help it powerfully remove pollutants.

When we used the best conditions (4.0 g/L of biochar and 180 minutes of contact time), our malt dust-derived biochar performed remarkably well in treating real greywater samples. The treatment significantly reduced key pollutants: Chemical Oxygen Demand (COD) dropped by about 85%, Total Suspended Solids (TSS) by roughly 90%, and turbidity (cloudiness) by around 95%. What's really important is that the treated greywater consistently met the requirements for Class B quality water according to the European Union (EU) 741/2020 wastewater reuse legislation. This means it's suitable for various non-drinking reuse applications, including watering certain crops in agriculture. Furthermore, our study reported an impressive 98.2% removal of organic material (BOD5) and 91.5% removal of pathogens (*E. coli*), showing the biochar's comprehensive cleaning power.

Looking at the economic side, we found significant practical benefits. Using biochar for greywater reuse led to an average 30% reduction in water consumption and a substantial cost saving of 377 EUR per month. This highlights how economically viable and cost-effective this approach is, making it an attractive alternative to traditional, energy-hungry treatment methods.

Beyond its direct cleaning ability, using agro-industrial waste to make biochar is a fantastic example of turning waste into something valuable. This contributes significantly to the idea of a circular economy, reducing waste and our carbon footprint. The findings of this research strongly suggest that agro-industrial biochar can play a vital role in easing global water scarcity, building stronger water systems, and supporting the bigger goals of the European Blue Deal and Green Deal.

To help this technology become widely adopted, future research should focus on scaling it up to continuous systems and pilot projects, exploring ways to regenerate the biochar, testing its effectiveness against new types of pollutants, and doing full environmental impact assessments. This study provides a solid foundation for continuing to develop and implement agro-industrial biochar as a sustainable and financially sound solution for water reclamation and reuse.

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