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Carbon filtration: harnessing cotton's power to purify drinking water

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ABSTRACT

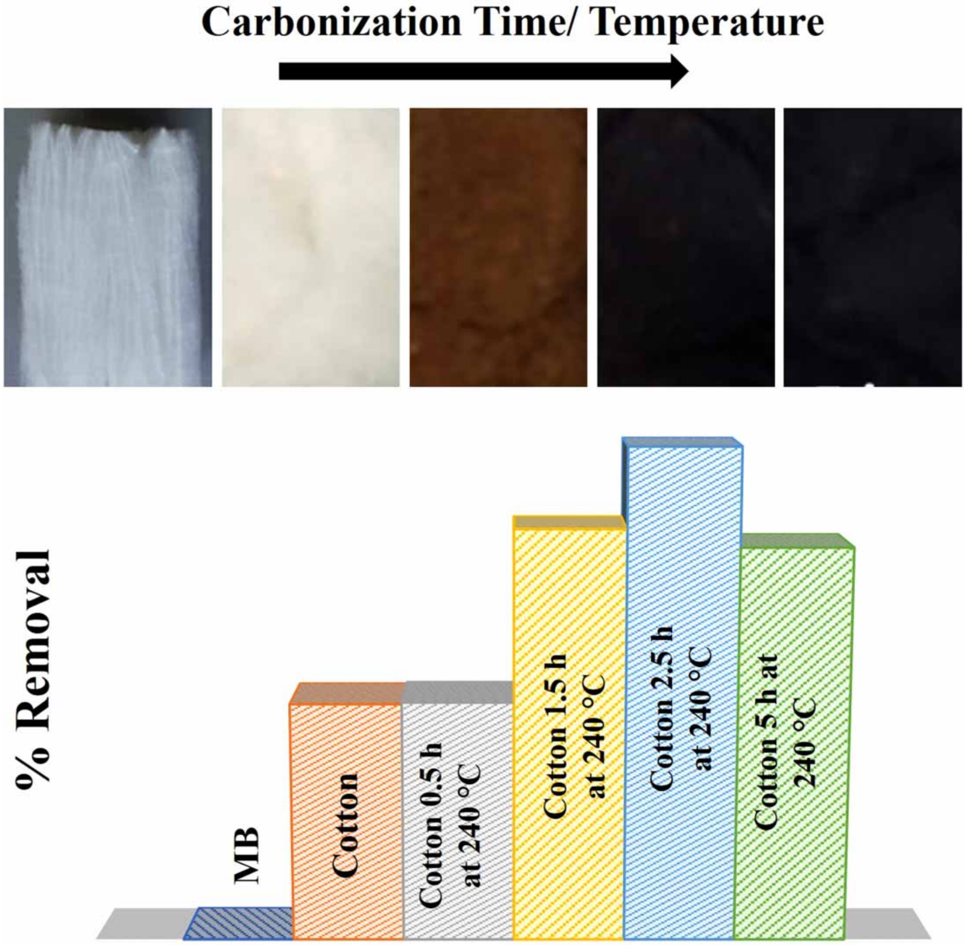
Water pollution is a global concern, necessitating accessible and effective water treatment solutions. Our study focused on developing and evaluating carbonized cotton filters for methylene blue (MB) removal from drinking water. We examined the impact of carbonization parameters on filter performance, revealing significantly higher MB removal with carbonized filters compared to pure cotton. This improvement can be attributed to increased surface area, enhanced adsorption capacity, and altered chemical properties resulting from carbonization. We also tested the generality of the process using lentils and sesame, further demonstrating the versatility of carbonized cotton filters. Additionally, we assessed filter durability through multiple filtration cycles, confirming their consistent efficiency over time. Our findings underscore carbonized cotton filters' efficacy and broad applicability for water purification, providing an affordable and sustainable solution to combat water pollution. This research advances water treatment technologies and advocates for using locally available resources to enhance water quality cost-effectively and eco-responsibly.

Key words: carbonized cotton, drinking water, filtration, methylene blue (MB), sustainable technology, water purification

HIGHLIGHTS

- *Emergency preparedness*: Carbonized cotton filters offer a reliable option for safe drinking water during critical situations.
- *Efficient water purification*: Carbonized cotton filters effectively remove methylene blue from drinking water, offering a sustainable solution.
- *Resource-accessible*: Utilizing locally available materials offers accessible water treatment solutions, especially in resource-limited settings.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Water is an indispensable resource for sustaining life, and ensuring its purity is paramount. With the increasing awareness of climate change, environmental degradation, and the potential occurrence of unforeseen events such as wars and earthquakes, the need for efficient filtration systems to purify drinking water, especially at the household level, has become ever more pressing (Diab *et al.* 2019, 2021). These circumstances highlight the significance of having reliable and accessible methods to ensure safe water supplies during times of uncertainty and emergencies, particularly for vulnerable populations, including those living in poverty (Sorenson *et al.* 2011; Pietrucha-Urbanik & Rak 2020; Salehi 2022). When basic necessities are scarce in times of crisis, reliable filtration systems become crucial for those facing challenges in regularly accessing clean water. The foundation of our research relies on using cotton as a primary raw material for carbonaceous material development. Cotton, one of the world's most abundant and easily accessible natural fibers, plays a pivotal role in our study (Dunne *et al.* 2016). Its extensive availability, particularly at the domestic nucleus or household level, underscores the practicality and relevance of our approach for a broad range of communities. Cotton's widespread cultivation and affordability make it a promising choice for ensuring access to clean drinking water, even in resource-constrained environments. Understanding the needs and circumstances of these disadvantaged communities is essential to designing and implementing effective emergency filtration systems tailored to their specific requirements, thus ensuring their access to safe drinking water during times of crisis. In addition to its significance for water purification in emergencies, removing dye molecules, such as methylene blue (MB), from drinking water is paramount due to their potential adverse health effects and environmental impacts (Fu & Viraraghavan 2000).

We have chosen MB as our target contaminant for several compelling reasons in this study. MB is a frequently encountered contaminant in wastewater due to its widespread use in various industrial processes, including textiles and medical diagnostics. Its presence in water sources can adversely affect human health and the environment, making it a relevant and concerning pollutant to address. Furthermore, MB serves as a well-established reference compound for assessing the performance of adsorption and filtration processes, providing a solid basis for our research. By focusing on MB removal initially, we aim to establish the effectiveness of our carbonized cotton filters as a proof of concept to expand their application to address a broader range of contaminants in future studies.

While significant progress has been made in water treatment technologies, including conventional methods such as filtration and biological treatment, as well as advanced processes like reverse osmosis and ultraviolet disinfection, their implementation in underserved regions with limited access to basic amenities remains challenging due to infrastructure requirements, energy consumption, and financial constraints (Naseem & Durrani 2021). Additionally, each method has its limitations: filtration requires regular cleaning and can experience membrane fouling, biological treatment can be expensive and time-consuming, reverse osmosis entails high investment costs, and UV disinfection necessitates a sufficient dose of UV light (Ang *et al.* 2015; Korotta-Gamage & Sathasivan 2017; Zhang *et al.* 2020).

Alternative and sustainable approaches are being explored to address this pressing issue, including using carbonized materials for water purification (Duan *et al.* 2017; Sartova *et al.* 2019; Iqbal *et al.* 2021; Liu *et al.* 2022). Carbonized materials, such as activated carbon and carbon nanotubes, are remarkably efficient at removing contaminants from water (Bolisetty & Mezzenga 2016; Sweetman *et al.* 2017). However, their high cost, need for high temperatures, and complex manufacturing processes restrict their applicability, particularly in resource-constrained environments. In this context, using low-cost and locally available materials for water treatment has emerged as a promising alternative. Cotton, an abundant and easily accessible natural fiber, holds great potential as a filtration material due to its inherent porosity and high adsorption capacity (Sweetman *et al.* 2017). Furthermore, cotton can be subjected to carbonization, which involves heating the material at high temperatures without oxygen, forming carbonized cotton filters.

This study focuses on developing and evaluating carbonized cotton filters to purify drinking water. By harnessing the carbonization process, we aim to enhance the filtration performance of cotton filters and enable the effective removal of contaminants such as MB from drinking water. We aim to provide a cost-effective and sustainable water treatment solution that can be applied in all circumstances, particularly for underserved populations. By utilizing readily available materials and simple manufacturing techniques, we aim to empower communities, including those with limited resources, to access clean drinking water. Furthermore, to demonstrate the generality and versatility of our proposed approach, we extended our study to include sesame and lentils, which are typical kitchen ingredients. This expanded the scope of our research to encompass a broader spectrum of potential water pollutants commonly found in household settings, aligning with our goal of providing a versatile and sustainable solution for diverse water treatment challenges.

The significance of this research lies in its potential to revolutionize water treatment practices by offering an affordable, sustainable, and accessible solution for purifying drinking water in diverse settings. By evaluating the efficiency and versatility of carbonized cotton filters, we can contribute to the global effort of achieving universal access to safe drinking water. Throughout this study, we will explore the impact of various carbonization parameters, such as temperature and duration, on the filtration performance of carbonized cotton filters. Additionally, we will assess the generalizability of the carbonization process by examining its effectiveness with other organic materials commonly found in everyday kitchens.

Ultimately, this research's findings promise to significantly advance water treatment technologies significantly, making clean drinking water accessible to communities in need. By prioritizing the needs of underserved populations, particularly those in poverty, we aim to contribute substantially to universal access to safe drinking water.

2. MATERIAL AND METHODS

2.1. Materials

In this study, we utilized a commonly available commercial cotton variety selected for its affordability and accessibility, aligning with our goal of providing a cost-effective water filtration solution. While the specific characteristics of commercial cotton may vary, our primary focus was on evaluating the impact of the carbonization process on the filtration properties of cotton. Multiple experimental runs were conducted using the same commercial cotton type to ensure our results' reliability and reproducibility. It is important to note that variations in cotton quality among different commercial products may exist, and these variations could potentially influence the properties of the resulting filters. MB (>95%) was purchased from Sigma-Aldrich. Cotton and deionized (DI) water (conductivity less than 0.1 μS/cm) were purchased from ROMICAL Ltd.

2.2. Carbonization process

The carbonization process involved the treatment of 1 g of commercial cotton in an autoclave at temperatures ranging from 160 to 240 °C for various durations (0.5–5 h), as illustrated in Figure 1. The heating rate was set at 10 °C/min, while the cooling was allowed to occur naturally. Furthermore, we extended our study to include sesame and lentils, two commonly available kitchen ingredients, demonstrating our carbonization approach's versatility and broad applicability. This expanded the scope of our research to encompass a broader range of organic materials that may be encountered in water sources, thereby providing a more holistic assessment of the filtration method.

2.3. Filtration process

A stock solution of MB, a dye molecule, was prepared by dissolving 100 mg of the dye powder in 50 mL of DI water. The concentration of the MB solution was adjusted to achieve an optical density (OD) at 664 nm of approximately 1. For the experiments, 110 μL of the MB stock solution was added to 50 mL of DI water.

As depicted in Figure 1, varying amounts of carbonized cotton were placed inside individual bags during the filtration process. Subsequently, each bag was added to a 50 mL tube containing 15 mL of the MB solution. The tube was then placed on a shaker and mixed at a speed of 150 rpm for 5 min.

2.4. Cost–benefit analysis

In evaluating the viability and applicability of the carbonized cotton filtration method, a comprehensive cost–benefit analysis has been conducted to provide insights into the economic aspects of the approach. This analysis considers material costs, labor, and equipment depreciation, aligning to create an affordable and accessible solution, particularly for resource-constrained communities.

2.4.1. Costs

- *Material costs*: Cotton, the primary material in the filtration method, is priced at approximately $1.40 for 100 g, translating to the cost per filter.
- *Energy costs*: The carbonization process involves heating the cotton inside an oven at 240 °C for 2.5 h, incurring an energy consumption cost of approximately $0.45 per filter.

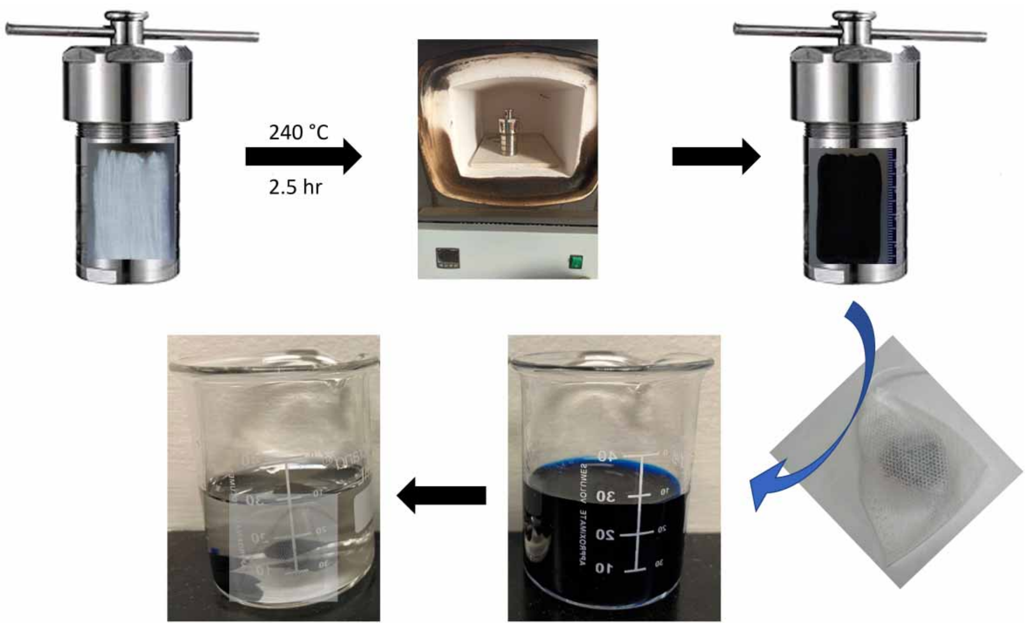


Figure 1 | Illustration of the carbonization process and the filtration of MB using the formed carbon.

- *Labor costs*: To ensure the method's feasibility for communities with limited resources, labor requirements have been minimized. The entire filter preparation takes less than 10 min, resulting in an estimated labor cost of $1.70 per filter based on a labor rate of $10 per hour.
- *Equipment depreciation*: Specialized equipment, such as the oven, plays a key role in our filtration process. A suitable oven for our method can be acquired for up to $80. Its useful life in terms of the number of filters it can produce before replacement is approximately 50 filters. Notably, the oven has demonstrated excellent durability, preparing more than 50 filters without needing replacement or significant maintenance. This durability underscores its cost-effectiveness in our filtration process, resulting in an equipment depreciation cost of $1.60 per filter.
- *Total cost per filter*: The total cost per filter is calculated by summing up the material costs, energy costs, labor costs, and equipment depreciation, resulting in a total cost of $4.15 per filter.

2.4.2. Benefit

The primary benefit of the approach lies in effectively removing contaminants, such as MB, from drinking water, contributing to improved public health and environmental protection. The benefit is expressed in terms of drinking water's enhanced quality and safety.

2.4.3. Cost–benefit ratio

To assess the cost-effectiveness of the method, the cost–benefit ratio is calculated by dividing the benefit by the total cost per filter.

Cost–benefit ratio = Benefit/Total cost per filter

The specific value of the cost–benefit ratio will depend on the context and location of implementation.

This cost–benefit analysis illustrates that while the method incurs costs related to materials, energy, labor, and equipment, it offers significant benefits in terms of water purification, which is crucial for public health and environmental sustainability. The cost–benefit ratio provides a quantitative measure of the economic feasibility of the proposed approach, aligning to make clean drinking water accessible to communities, including those with limited resources. This analysis serves as a valuable tool for assessing the economic viability of the proposed filtration method in various settings, emphasizing its potential for positive societal impact.

2.5. Experimental design

The experimental design aimed to determine the optimal carbonization temperature for cotton filters that remove MB from water. A series of experiments were conducted, including temperatures of 160, 200, and 240 °C, each for 2.5 h. The effect of different carbonization times was explored, including 0.5, 1.5, 2.5, and 5 h. These temperature and time combinations were selected based on prior research and a preliminary study indicating their relevance for the carbonization of natural fibers. The resulting filters were characterized by assessing their MB removal efficiency after carbonization. Multiple replicates were performed for each temperature and time combination to ensure the reliability of the findings. Furthermore, the performance of the filters over multiple additive cycles was examined to evaluate their long-term effectiveness in removing MB.

3. RESULTS AND DISCUSSION

Our investigation aimed to evaluate the influence of various parameters, including pure cotton, carbonization temperature, duration time, and kinetic factors, on the effectiveness of carbonized cotton as a filtration material for removing MB from drinking water, chosen as a model organic contaminant.

The initial experiments focused on using pure cotton as a filtration material to remove MB from drinking water. The results revealed that pure cotton's efficiency was limited, with lower removal rates observed. For instance, using a lower amount of cotton (20 mg), approximately 37% of the initial MB contaminants were removed. However, when a higher amount of cotton (200 mg) was employed, the removal efficiency improved to approximately 78%, as shown in Figure 2(a) and Supplementary Table S1. The results highlight the necessity to enhance the filtration percentages when using pure cotton alone. To address this limitation and consider the goal of developing a filter suitable for uncertainty and emergencies, the carbonization of cotton emerges as a promising approach. By subjecting cotton to a low-temperature carbonization process, we can significantly improve the filtration efficiency while maintaining the feasibility of production under resource-limited conditions.

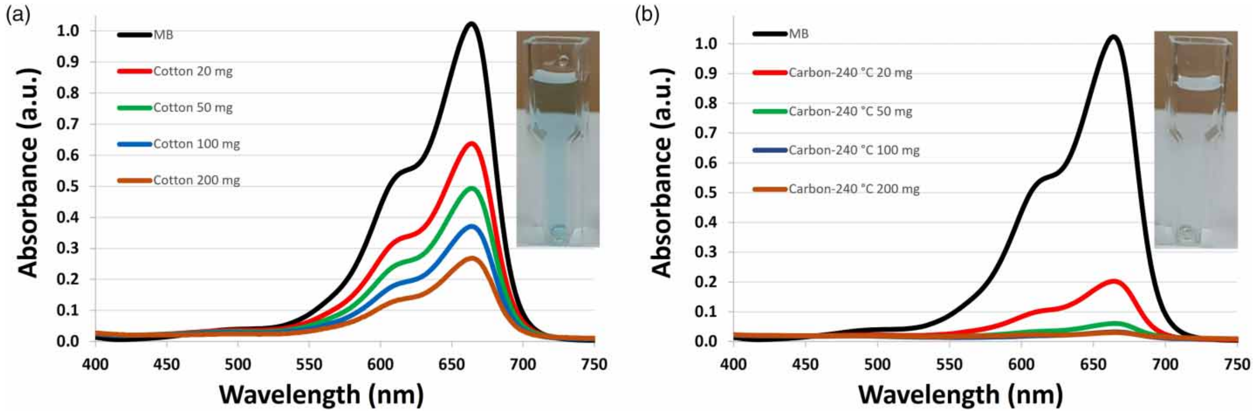


Figure 2 | Optical properties of MB solutions with varying concentrations of cotton (a) and carbon (b) after 5 min of mixing. The insets show optical images of the MB solution after filtration using 200 mg of cotton and carbon. Cotton-mixed MB solutions retain a blue color, indicating residual dye presence. Conversely, carbon-mixed MB solutions are colorless, demonstrating superior purification capability.

To address the limitations observed in the filtration efficiency of pure cotton alone and to prevent cotton and carbon suspension in the final water while ensuring the efficient removal of MB and maintaining water clarity, the filters were placed inside bags, as shown in Figure 1.

The carbonization process was conducted at 240 °C inside an autoclave for 2.5 h. The resulting carbonized filters showed a remarkable performance improvement compared to pure cotton filters. Figure 2(b) and Supplementary Table S1 present the results of the filtration experiments using carbonized material. It clearly illustrates that when utilizing 20 mg of carbonized material, an impressive 80% removal of MB was achieved. This represents a substantial 121% enhancement in the filtration efficiency compared to the same quantity of pure cotton. Moreover, with the increased dosage of 200 mg of carbonized material, the removal efficiency surpassed 99%, demonstrating a significant advancement in filtration capability.

The higher removal efficiency observed with carbonized cotton than pure cotton can be attributed to several reasons. First, carbonization increases the surface area, providing more active sites for the adsorption of contaminants (Titirici & Antonietti 2010). Second, the carbonization process creates micropores and mesopores, enhancing the adsorption capacity of the material (Xu *et al.* 2021). Third, the formation of carbon-based functional groups on the surface through carbonization improves the chemical properties of the cotton, leading to a stronger affinity for contaminants (Xu *et al.* 2021). Lastly, the more porous structure of carbonized cotton reduces filtration resistance, allowing for better flow dynamics and improved contact between the material and contaminants (Shen *et al.* 2014).

Building upon these findings, the subsequent sections of this paper present a comprehensive investigation of the carbonization process, the adsorption processes kinetics, and the method's generalizability. Furthermore, we investigate to determine the carbonized filter's maximum capacity and assess its performance with other contaminants, such as olive waste mill. Through these investigations, we aim to provide a comprehensive understanding of the carbonization process and its applications, highlighting its effectiveness and potential in water filtration systems.

Understanding the influence of carbonization temperature on the performance of carbonized cotton filters is crucial in optimizing their efficacy for water filtration. Thus, we conducted a series of experiments varying the durations (0.5–5 h) at 240 °C, as shown in Figure 3 and Supplementary Table S2. Figure 3(a) presents an optical image of the prepared filters, displaying the change in cotton color as a function of carbonization duration: white at 0.5 h, brown at 1.5 h, brown-black at 2.5 h, and black at 5 h. Figure 3(b) and Supplementary Table S2 illustrate the absorbance of MB remaining in the solution after filtration through 20 mg of carbonized cotton filters prepared at different durations. All filters were mixed with MB solutions for 5 min, followed by absorbance measurement. The inset in Figure 3(b) shows the percentage of MB removal from the solutions using the carbonized cotton filters.

Furthermore, our results demonstrated that the removal efficiency of MB increased with the increase in carbonization time until 5 h, after which it started to decrease. The optimal carbonization duration was 2.5 h, where the removal efficiency significantly improved from 40 to 80%. However, at 5 h, the removal efficiency was reduced to 65%, indicating a non-linear

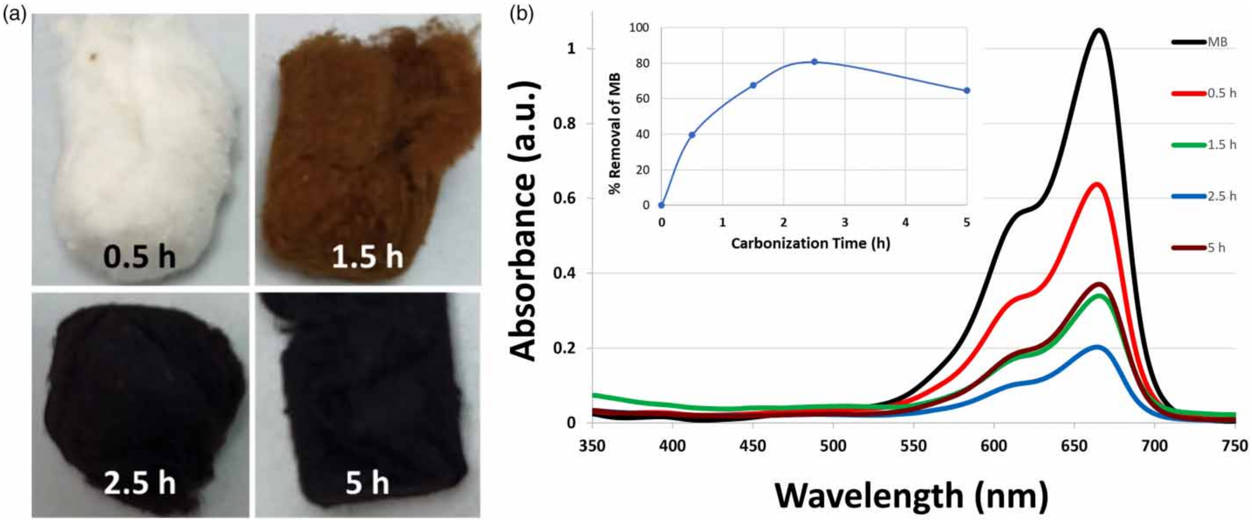


Figure 3 | Optical image of prepared filter (a) and absorbance of MB remaining in the solution after filtration through carbonized cotton filters (b) prepared at 240 °C for different durations: 0.5, 1.5, 2.5, and 5 h. All filters prepared for different durations were mixed with MB solutions for 5 min, followed by absorbance measurement. The inset shows the percentage of MB removal from the solutions using the carbonized cotton filters.

relationship between carbonization time and MB removal efficiency. Notably, throughout all the investigations presented in this study, a fixed amount of 20 mg of carbonized cotton was used.

The carbonized cotton removal efficiency from 0.5 to 2.5 h can be attributed to the previously explained factors, including the increased surface area, the presence of functional groups, and enhanced porosity. However, the observed reduction in removal capability when the cotton was carbonized for a prolonged time (5 h) can be referred to as the excessive formation of carbon-based structures and increased density. This leads to a decrease in porosity and surface area, which are critical for the effective adsorption of contaminants, consequently reducing the adsorption capacity and removal efficiency (Qiu *et al.* 2015). Additionally, extended carbonization times increase the likelihood of pore agglomeration or block within the carbonized cotton material, resulting in restricted water flow and hindered contact between the filter and contaminants, diminishing the effectiveness of the filtration process. Moreover, prolonged exposure to high temperatures during carbonization can induce significant structural changes in the cotton material, leading to the formation of denser carbon structures or the collapse of existing pore structures, further reducing the adsorption capacity and removal efficiency.

We also investigated the impact of different carbonization temperatures (160, 200, and 240 °C) on the removal efficiency of MB from drinking water, as shown in Figure 4(a) and Supplementary Table S3. The objective was to identify the minimum temperature required to achieve satisfactory removal efficiency. Interestingly, the results exhibited similar behavior to the effect observed with the varying duration of carbonization at 240 °C. The removal efficiency increased with rising temperatures, indicating that higher temperatures favor improved filtration performance. Notably, the maximum efficiency was achieved at 240 °C, similar to the previous findings. The removal efficiency increased from 40% at 160 °C to 65% at 200 °C and improved to 80% at 240 °C when 20 mg of carbonized cotton was mixed with 15 mL of MB solutions (OD = 1). These results align with the earlier observations on the effect of duration, where carbonization for 0.5 h at 240 °C resulted in an efficiency of 37%, 1.5 h led to 66%, and 2.5 h resulted in 80% removal efficiency. While our study found that a carbonization temperature of 240 °C yielded optimal results for our specific objectives, it is worth noting that different temperatures could be explored in settings with access to advanced equipment and inert atmospheres. However, our approach at 240 °C provides a practical and effective solution for communities with limited resources. We have also developed a method that allows carbonization without an inert atmosphere, making it more accessible in resource-constrained environments.

To further examine the effect of filtration cycles, we utilized the same 20 mg of carbonized cotton (carbonized for 2.5 h at 240 °C) in consecutive baths of 15 mL MB solution (OD = 1), as presented in Figure 4(b) and Supplementary Table S3. At each step, we measured the absorbance of the remaining MB in the solution before moving the used filter to a fresh batch

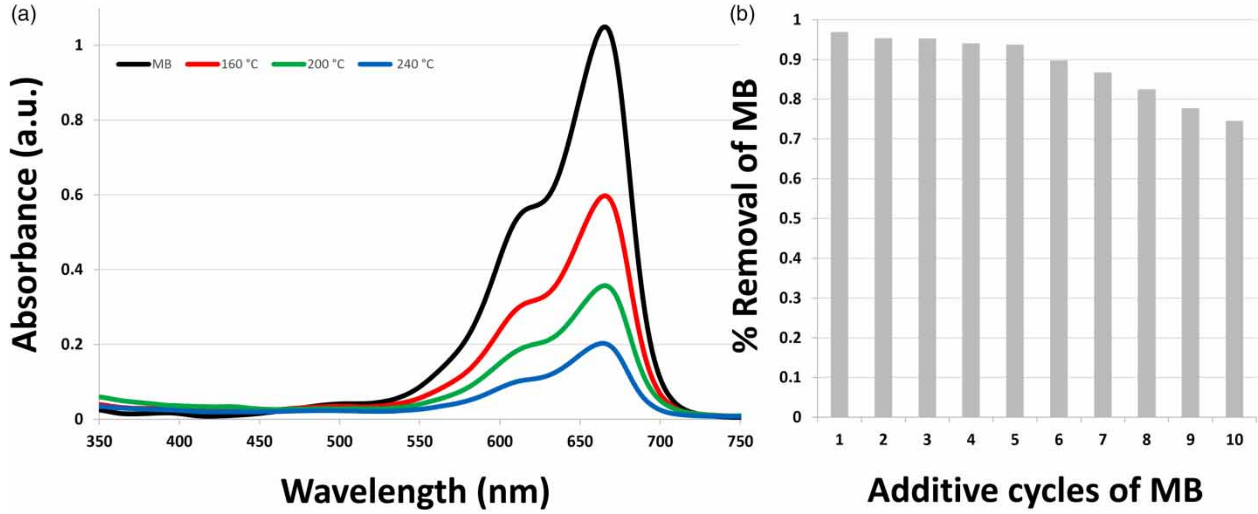


Figure 4 | (a) Comparison of MB absorbance before and after mixing with 20 mg of carbonized cotton at different temperatures (160, 200, and 240 °C). All mixings were performed for 5 min. (b) The repeated use of the same filter (20 mg, 2.5 h at 240 °C) for 10 cycles using the fresh MB solution showcases the filter's durability and consistent removal efficiency.

of the MB solution. This process was repeated for a total of 10 cycles. The results revealed that the filter's efficiency in removing MB remained consistently high throughout the initial cycles, with removal rates above 94% until cycle number 5. However, beyond cycle 5, a gradual reduction in the removal efficiency was observed, reaching approximately 75% by cycle 10.

The kinetic study was conducted using a 200 mg filter of carbonized cotton prepared at 2.5 h and 240 °C to provide a more extensive filtration volume and minimize errors associated with aliquot sampling. By scaling up the process to use 150 mL of MB solution (OD = 1), the error introduced by taking an aliquot of only 1.5 mL was reduced to less than 1%. This ensured a more accurate assessment of the reaction kinetics and improved the reliability of the results.

Utilizing a larger filtration volume enabled a more comprehensive evaluation of the carbonized cotton filter kinetic behavior of MB removal. To track the rate of MB degradation and observe the first-order reaction's progress, the MB solution's optical properties were measured at various time intervals, as shown in Figure 5 and Supplementary Table S4. This approach provided valuable insights into the kinetics of the adsorption process and the effectiveness of the carbonized cotton filter in removing MB from the solution. We observed that the absorbance of the remaining MB in the solution decreased with time, indicating the progressive removal of MB by the carbonized cotton filter. After approximately 12 min, the absorbance reached a plateau, suggesting the attainment of equilibrium and indicating no significant improvement in MB removal beyond this time. At equilibrium, a removal efficiency of 97% was achieved, demonstrating the high effectiveness of the carbonized cotton filter. To determine the order of the adsorption process, we performed a fitting to the first-order reaction model. The inset in Figure 5 presents the well-agreed fitting to the first-order reaction equation, $\ln[A] = -kt + \ln[A]_0$, with an excellent coefficient of determination (R^2) value of 0.996. This analysis further confirms the first-order nature of the adsorption kinetics and underscores the suitability of the first-order reaction model in describing the MB removal by the carbonized cotton filter. The rate constant (k) was determined to be 0.285 min^{-1}, indicating the first-order reaction rate.

To demonstrate the generality of the process and the ability of carbonization to remove MB from other organic molecules commonly found in kitchens, lentils and sesame were used as examples. These organic materials, often accessible to individuals with limited resources, were subjected to carbonization. The carbonized lentils and sesame demonstrated notable efficiency in removing MB from the solution, indicating the broad applicability of carbonization for water treatment. Figure 6(a) visually confirms the successful carbonization process of lentils and sesame, as evidenced by the color change from orange or white to black after heating for 2.5 h at 240 °C inside an autoclave.

However, it is essential to acknowledge that the removal capabilities of the carbonized lentils and sesame were limited. Lentils exhibited a removal efficiency of only 12%, while sesame showed a slightly higher removal efficiency of approximately 50%, as demonstrated in Figure 6(b) and Supplementary Table S5. This lower efficiency can be attributed to oily molecules in

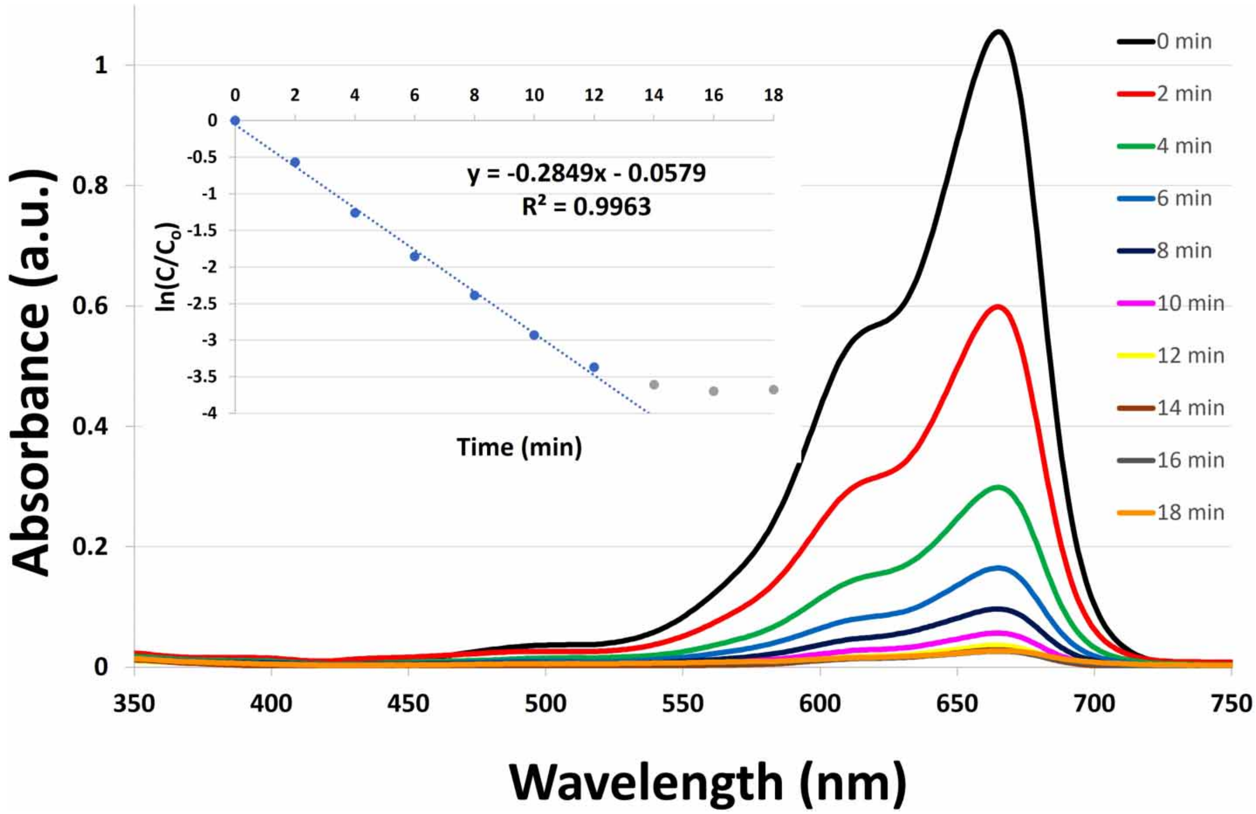


Figure 5 | The optical properties of the MB solution were analyzed by sampling at different time intervals during the filtration process. The inset demonstrates a kinetic study that exhibits a well-fitted curve, indicating a first-order reaction model.

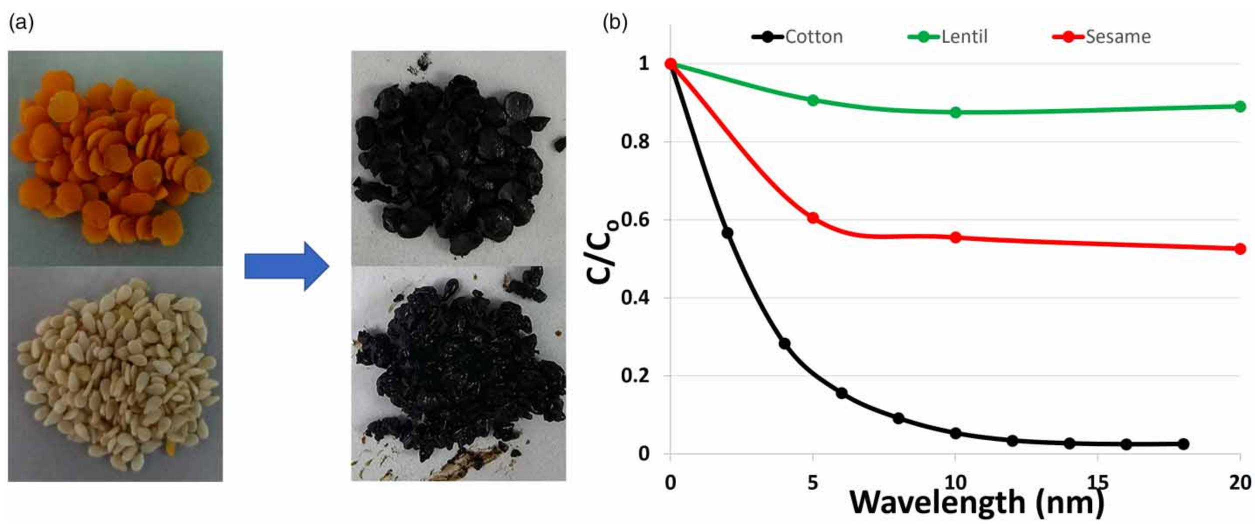


Figure 6 | The generality of the carbonization process. (a) Optical image depicting the visual transformation of sesame and lentils before and after the carbonization process. (b) Normalized concentration of MB after filtrations at $\lambda = 665$ nm, where C and C_0 represent the MB concentration at time t and its initial concentration, respectively.

the carbonized phase, as depicted in the optical image in Figure 6(a). These oily molecules may require higher temperatures for complete conversion into carbon, thus affecting the filtration performance. Furthermore, it is noteworthy that sesame demonstrated better removal capabilities than lentils, suggesting variations in the composition or structural properties of the carbonized materials. Further investigation is warranted to explore the factors contributing to this discrepancy and optimize the filtration performance of different organic materials for water treatment applications.

4. CONCLUSIONS

This study has explored the potential of carbonized cotton filters as a cost-effective and sustainable solution for water purification, with a particular emphasis on removing MB from drinking water. Through experiments and analyses, we have demonstrated the enhanced filtration performance of carbonized cotton filters compared to pure cotton, highlighting their increased surface area, improved adsorption capacity, and consistent removal efficiency.

Furthermore, our research has emphasized the versatility of the carbonization process, showcasing its successful application to other organic materials commonly found in kitchens, such as lentils and sesame. This broadens the scope of our approach and underscores the potential for utilizing locally available resources in water treatment, especially in resource-constrained settings.

In addition to the technical aspects, we have conducted a comprehensive cost–benefit analysis, considering the cost of raw materials, energy consumption, labor, and equipment depreciation. Our analysis supports the economic feasibility of carbonized cotton filters, positioning them as a viable alternative to conventional water purification methods, particularly in regions with limited resources.

Overall, our findings highlight the promise of carbonized cotton filters as a practical and accessible means of improving water quality, addressing the challenges of waterborne contaminants, and contributing to the global goal of ensuring universal access to safe drinking water. By combining enhanced filtration performance with affordability, our research has the potential to revolutionize water treatment practices and positively impact public health.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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