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Comparative Effectiveness of Durian Peel and Coconut Shell Charcoal Biofilters for Calcium Carbonate Reduction in Groundwater: Experimental Study in Palu City

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ABSTRACT

Introduction: Water hardness caused by high concentrations of calcium carbonate is a persistent problem in many groundwater-dependent communities, including Palu City, Central Sulawesi, Indonesia. Excessive hardness reduces water acceptability, increases household maintenance costs, and contributes to scaling in pipes and storage systems. This study aimed to evaluate the effectiveness of two locally available organic-waste materials—durian peel charcoal and coconut shell charcoal—as low-cost biofilter media for reducing calcium carbonate concentrations in household well water.
Method: A laboratory-based experimental design was applied using batch adsorption methods. Groundwater samples with an initial calcium carbonate concentration of 568 milligrams per litre were treated with varying masses of each adsorbent and different contact times. The study examined combinations of adsorbent mass and exposure time to determine optimal operating conditions. Calcium carbonate levels before and after treatment were measured using standard titration techniques to assess removal efficiency.
Results: The results demonstrated that both organic-waste biofilters were capable of substantially lowering hardness levels. Durian peel charcoal achieved its best performance at a moderate adsorbent mass and short contact time, showing rapid adsorption kinetics and high affinity for hardness-related ions. Coconut shell charcoal also produced significant reductions but required greater mass and longer contact time to reach optimal effectiveness. The findings confirmed that adsorption performance was nonlinear and strongly influenced by operational parameters, material characteristics, and initial contaminant concentration. Comparison of the two media indicated that each possesses distinct advantages, highlighting the importance of context-specific optimisation for practical application.
Conclusion: Overall, the study shows that transforming locally abundant agricultural wastes into biofilter media offers a feasible and affordable strategy for decentralised water treatment. The research contributes new comparative evidence on the use of durian peel and coconut shell charcoal for hardness reduction and supports their potential use in household-scale systems. If validated under field conditions, these findings may support the development of affordable household-scale strategies for improving the acceptability of drinking water in resource-limited communities.

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INTRODUCTION

Access to safe and acceptable drinking water remains a fundamental public health priority worldwide. Among the numerous parameters that determine the suitability of water for domestic use, water hardness—primarily caused by elevated concentrations of calcium carbonate ($CaCO_3$)—has long been a subject of scientific and regulatory concern. Excessive hardness in groundwater and household well water is widely reported in many regions and is associated with a range of health, environmental, and economic implications. From a health perspective, the relationship between water hardness and human health outcomes has been debated for several decades. Systematic reviews suggest that higher levels of hardness may have potentially protective associations with cardiovascular disease, although direct causal relationships remain inconclusive (1). Furthermore, elevated concentrations of calcium and carbonate ions influence the sensory characteristics of water, affecting taste and consumer acceptability (2,3). These considerations indicate that hardness is not merely a technical water quality parameter, but also an issue closely linked to public perception and everyday household practices.

In addition to health-related aspects, the environmental and infrastructural impacts of high $CaCO_3$ concentrations are substantial. Hard water contributes to scale formation in pipes, storage tanks, and distribution networks, which ultimately reduces flow efficiency, increases corrosion risks, and shortens the operational lifespan of water infrastructure. Scaling also affects energy consumption in heating systems and treatment processes, thereby creating indirect environmental burdens (4,5). From an economic standpoint, these problems translate into increased maintenance costs for households and public utilities. Water hardness accelerates the build-up of deposits in plumbing systems and raises the costs required for cleaning, replacement, and chemical treatment. Moreover, initiatives aimed at calcium fortification or water softening must carefully consider consumer acceptance and cost-effectiveness (2,3). Consequently, international and national water quality standards regulate hardness and $CaCO_3$-related parameters through guidelines based on palatability thresholds, corrosion control, and infrastructure protection (3,6). These regulatory frameworks integrate multidisciplinary evidence from chemistry, toxicology, and public health to ensure limits that are both feasible and protective (3,4).

Despite the widespread availability of regulatory guidance, many communities—particularly in low- and middle-income countries, including Indonesia—continue to face difficulties in meeting recommended hardness levels due to limited access to centralised water treatment systems. This challenge is highly relevant to the local context of Palu City, Central Sulawesi Province, where a large proportion of the population still relies on groundwater and dug wells as their primary sources of clean water. The hydrogeological characteristics of the Palu region, which are dominated by carbonate and alluvial formations, create a high potential for elevated $CaCO_3$ content in household well water, making water hardness a tangible problem at the community level. Conventional water softening technologies, such as lime–soda precipitation and ion exchange, are effective and reliable; however, they require substantial capital investment, technical expertise, and continuous operational inputs (7). These requirements often render conventional methods impractical for rural and peri-urban communities surrounding Palu City that depend on decentralised groundwater sources and have limited economic and technical capacity. As a result, there is growing interest in low-cost, community-based water treatment alternatives that can be implemented using locally available resources in Central Sulawesi. Decentralised approaches that utilise adsorption processes and simple filtration systems offer promising opportunities for reducing water hardness with minimal infrastructure requirements and are more compatible with the socio-economic conditions of Palu and its surrounding areas (8).

Low-cost adsorbent technologies derived from agricultural residues and organic waste have emerged as particularly attractive solutions. Community-based treatment systems employing biochar and other plant-derived adsorbents are capable of removing hardness-causing species as well as various other contaminants through relatively simple configurations. The effectiveness of these methods is strongly influenced by critical operational parameters such as adsorbent quality, contact time, and the ability to regenerate the media. Such approaches provide significant advantages in terms of affordability, accessibility, and adaptability to local contexts, although their long-term reliability requires sustained community engagement and adequate technical capacity (8). In contrast, conventional chemical softening methods deliver higher throughput and more predictable performance but are accompanied by higher operational costs and centralised logistical demands (7). Recent perspectives indicate that integrating low-cost adsorbents as a pre-treatment stage can reduce the burden on conventional processes and lower overall treatment costs in resource-limited communities (7).

Among the various materials investigated for decentralised water treatment, agricultural by-products and organic wastes demonstrate considerable potential as sustainable adsorbents. Feedstocks such as rice husks, coconut shells, and other lignocellulosic residues possess intrinsic physicochemical properties that make them suitable for contaminant removal. Biochars produced from these materials exhibit adsorption capacity for hardness-related ions, heavy metals, and organic pollutants, thereby offering abundant and inexpensive options for rural water treatment systems (9). Systematic reviews emphasise that sustainable adsorbents derived from agricultural waste can play an important role in community-scale water purification, although performance varies depending on contaminant type and material characteristics (8). Empirical studies further confirm that simple, locally sourced materials can enhance water quality in both pilot and field applications (9).

The effectiveness of plant-based biochars and activated carbons in hardness removal is supported by well-established adsorption mechanisms. Physical adsorption and pore diffusion processes enable Ca^{2+} and Mg^{2+} ions to interact with carbon surfaces through ion–dipole interactions, hydrogen bonding, and van der Waals forces. Materials with high surface area and hierarchical porosity generally exhibit superior uptake kinetics and adsorption capacity (10). In addition, ion-exchange and surface complexation mechanisms play a crucial role. Functional groups such as carboxyl and phenolic moieties on biochar surfaces facilitate cation exchange and inner-sphere complex formation, effectively reducing dissolved hardness species (10). Modifications through chemical activation or heteroatom doping can further enhance affinity for calcium ions and improve regeneration potential (10–12). These mechanistic insights provide a robust scientific foundation for the development of biofilter media from locally available organic wastes.

Within the existing body of research, two materials of particular relevance in tropical regions are durian peel charcoal and coconut shell charcoal. Both are generated in large quantities as agricultural wastes and possess structural properties favourable for adsorption applications. However, the available literature reveals important gaps regarding the comparative performance of these materials for hardness removal. Most previous studies have focused on the removal of dyes, heavy metals, or organic contaminants rather than on Ca^{2+} and carbonate-related hardness parameters (10). Direct, side-by-side evaluations of durian peel and coconut shell media under identical groundwater conditions remain limited, particularly with respect to adsorption kinetics, optimal operating conditions, and regeneration efficiency. Moreover, information on long-term column performance, fouling behaviour, and practical feasibility at the household scale is still scarce (10). Comprehensive life-cycle and economic evaluations comparing the two materials are also largely lacking, despite their importance for community-level implementation (10–12)

These gaps underscore the need for systematic investigation into the effectiveness of locally sourced organic waste biofilters for reducing $CaCO_3$ concentrations in real groundwater matrices. In many regions, including several areas of Indonesia, communities rely heavily on shallow wells where hardness frequently exceeds recommended standards. Therefore, identifying simple, affordable, and environmentally sustainable treatment options is of critical importance. The present study seeks to address this need by experimentally evaluating the performance of durian peel charcoal and coconut shell charcoal as biofilter media for hardness reduction in household well water. The study aims to determine optimal operational parameters—specifically biofilter mass and contact time—and to compare the relative effectiveness of the two materials under controlled laboratory conditions.

Accordingly, the objectives of this research are: (1) to assess the capability of durian peel charcoal and coconut shell charcoal to reduce $CaCO_3$ concentrations in well water; (2) to analyse the influence of biofilter mass and contact time on treatment effectiveness; and (3) to identify the most efficient configuration for practical household application. The novelty of this study lies in its direct comparative approach using identical experimental conditions and real groundwater samples, thereby generating empirical evidence that can inform low-cost, community-based water treatment strategies. The scope of the research is limited to laboratory-scale batch experiments focusing on $CaCO_3$ reduction; nevertheless, the findings are expected to contribute to the development of sustainable and locally adaptable solutions for improving drinking water quality in resource-constrained settings.

METHOD

Research Design

This study employed an experimental laboratory-based approach to evaluate the effectiveness of organic waste–derived biofilters in reducing calcium carbonate ($CaCO_3$) concentrations in well water. The experimental design followed a structured batch adsorption framework, which is widely used for the preliminary assessment of adsorbent performance, kinetic behaviour, and equilibrium characteristics. Batch studies are recognised as efficient tools for rapid screening of adsorbent materials prior to more complex fixed-bed or pilot-scale applications (13). The design of the present research was oriented toward determining the influence of two primary operational variables—adsorbent mass and contact time—on $CaCO_3$ removal efficiency.

To ensure systematic evaluation, the study adopted a factorial arrangement of experimental conditions. Factorial and response surface methodologies are recommended for adsorption studies because they enable the simultaneous assessment of multiple variables and their interactions with a manageable number of experimental runs (14,15). Although a full response surface optimisation was beyond the scope of this study, the experimental layout was organised to reflect the principles of design of experiments (DoE), allowing the identification of optimal combinations of mass and contact time. Such approaches have been shown to efficiently identify variable interactions and performance optima while reducing unnecessary experimentation (15,16).

Study Location and Water Sampling

The research was conducted using groundwater samples collected from household wells in Palu City, Central Sulawesi, Indonesia. Palu represents an appropriate study setting due to the widespread reliance on shallow wells and the frequent occurrence of high-water hardness in the region. Water samples were obtained from a residential well located in the Mantikulore district, an area known to exhibit elevated $CaCO_3$ concentrations. Samples were collected in clean polyethylene containers following standard procedures to prevent contamination and were transported immediately to the Environmental Health Laboratory of Universitas Muhammadiyah Palu for analysis.

Baseline measurements were performed to determine the initial $CaCO_3$ concentration and general water quality characteristics. Initial hardness values exceeded national guideline limits, confirming the relevance of the site as a case study for evaluating decentralised treatment options. All experimental procedures were carried out under controlled laboratory conditions to minimise external variability.

Preparation of Biofilter Media

Two types of organic waste materials were selected as adsorbent media: durian peel charcoal (Durio zibethinus) and coconut shell charcoal (Cocos nucifera). These materials were chosen due to their local availability in Central Sulawesi and their documented potential as low-cost adsorbents. Raw materials were cleaned, dried, and carbonised using conventional pyrolysis procedures to produce charcoal with adequate porosity and surface characteristics. After carbonisation, the adsorbents were crushed and sieved to obtain uniform particle sizes suitable for batch adsorption experiments.

The selection of these materials was informed by established adsorption mechanisms reported for plant-based biochars and activated carbons. Physical adsorption through pore diffusion, ion–dipole interactions, and surface complexation have been identified as key processes in hardness removal (10). Functional groups such as carboxyl and phenolic moieties on biochar surfaces facilitate cation exchange with Ca^{2+} and Mg^{2+} ions, thereby reducing dissolved hardness species (10–12). These theoretical considerations provided the scientific rationale for the use of durian peel and coconut shell charcoal as biofilter media.

Experimental Procedure

Batch adsorption experiments were conducted to evaluate the performance of each adsorbent under varying operational conditions. Two independent variables were investigated:

1. Adsorbent mass: 60 g, 80 g, and 100 g
2. Contact time: 5 minutes, 10 minutes, and 15 minutes

For each experimental run, a fixed volume of well water was mixed with the designated mass of adsorbent in a clean container and agitated manually to ensure adequate contact between the water and the biofilter media. After the specified contact time had elapsed, the mixture was filtered, and the treated water was collected for $CaCO_3$ analysis. All experiments were performed in triplicate to enhance reliability and minimise random error.

The use of batch experiments as an initial assessment stage is consistent with common practice in adsorption research, where such designs are utilised to generate data for kinetic and equilibrium evaluation prior to potential scale-up in fixed-bed systems (Jurado-Davila et al., 2023). While column studies are valuable for understanding breakthrough behaviour and real filter performance, batch methods provide essential foundational information on material effectiveness and operational feasibility.

Analytical Methods

Accurate determination of $CaCO_3$ concentrations is essential for evaluating treatment performance. In this study, $CaCO_3$ levels were quantified using standard titrimetric methods based on total hardness and alkalinity measurements. Direct assessment of carbonate hardness through titration remains one of the most widely applied laboratory techniques due to its practicality and reliability when performed with calibrated reagents and buffers (5,6)

Total hardness was used as a proxy indicator of Ca^{2+} and Mg^{2+} concentrations, following established analytical approaches. Advanced instrumental techniques such as ICP-OES and AAS are commonly used for precise ion analysis, while indices such as the Langelier Saturation Index (LSI) and Ryznar Stability Index are frequently applied to evaluate scaling potential (5,6). Although these sophisticated techniques were not available for the present study, standard titration procedures provided reliable and appropriate measurements for comparative performance evaluation.

Indirect measurement approaches, including ion-selective electrodes for calcium and magnesium, have also been reported as dependable when properly calibrated (17,18). However, the titrimetric method was selected due to its suitability for routine laboratory use and its alignment with national water quality testing practices.

Determination of Optimal Conditions

The identification of optimal adsorbent mass and contact time is a critical aspect of adsorption-based treatment design. In adsorption research, optimal parameters are commonly determined through kinetic and isotherm modelling, which enable estimation of adsorption capacity and rate-limiting steps (19,20). Although detailed mathematical modelling was not performed in the current study, the experimental configuration was structured to allow empirical comparison of removal efficiencies across different conditions.
Design of experiments (DoE) and response surface methodologies are widely recommended for exploring interactions between operational variables and locating optimum treatment conditions with quantified uncertainty (15,16). The present research applied these principles conceptually by testing multiple combinations of mass and time in order to identify the configuration that produced maximum $CaCO_3$ reduction with minimal resource input.
In larger-scale applications, fixed-bed column experiments are typically used to optimise bed depth, residence time, and service life through analysis of breakthrough curves (13). While such dynamic studies were beyond the scope of this laboratory investigation, the findings from the batch experiments provide essential baseline information for future column design and community-level implementation.

Data Analysis
Data obtained from the experiments were analysed descriptively to compare pre- and post-treatment $CaCO_3$ concentrations for each combination of adsorbent type, adsorbent mass, and contact time. Removal efficiency was calculated as the percentage reduction relative to the initial hardness concentration. The results were tabulated and interpreted to identify the treatment configuration that produced the greatest observed reduction for each biofilter material.
Because the present study was designed as a preliminary laboratory-based assessment, inferential statistical testing was not performed. Therefore, differences among treatment combinations were interpreted based on observed removal patterns rather than statistical significance. Future studies with larger experimental replication and formal statistical modelling are recommended to validate differences between adsorbent type, adsorbent mass, contact time, and their interaction effects.
Through this systematic methodology, the study aimed to generate preliminary and locally relevant laboratory evidence regarding the feasibility of using durian peel charcoal and coconut shell charcoal as low-cost options for hardness reduction in the specific context of Palu City, Central Sulawesi.

RESULTS

Baseline Characteristics of Well Water in Palu City
The initial stage of the study focused on establishing the baseline quality of groundwater collected from a household well in Palu City, Central Sulawesi, Indonesia. Baseline assessment is essential in adsorption-based treatment research because the initial contaminant concentration strongly influences observed removal efficiency and the interpretation of biofilter performance. Higher influent concentrations can generate greater absolute removal but may reduce percentage removal when adsorbent capacity is limited, thereby affecting comparisons across different media (14,15).
Regional surveys in tropical and developing-country contexts commonly report drinking-water hardness within a range of approximately 60–300 mg/L as $CaCO_3$, with many values clustering around 100–200 mg/L depending on local hydrogeological conditions. These ranges are frequently used as reference points when evaluating palatability, scaling potential, and corrosion risk in water distribution systems. The groundwater sample analysed in the present study, however, exhibited substantially higher hardness, reflecting the carbonate-rich geological characteristics of the Palu region.

Table 1. Baseline Quality of Groundwater Used in the Study

Parameter	Measured Value	Typical Range in Tropical Regions
Calcium carbonate ($CaCO_3$)	568 mg/L	60–300 mg/L

Table 1 presents the initial condition of the well water used in the experiments. The measured concentration of 568 mg/L $CaCO_3$ clearly exceeds typical values reported for tropical groundwater and is well above commonly accepted drinking-water thresholds. This elevated baseline confirms the relevance of evaluating effective hardness-reduction methods for communities in Palu City.

Experimental Configuration for Biofilter Testing
Prior to presenting treatment outcomes, the structure of the experimental design is illustrated in diagrammatic form to clarify the relationship between adsorbent type, mass, and contact time. A factorial arrangement was used to explore performance trends for both durian peel charcoal and coconut shell charcoal.

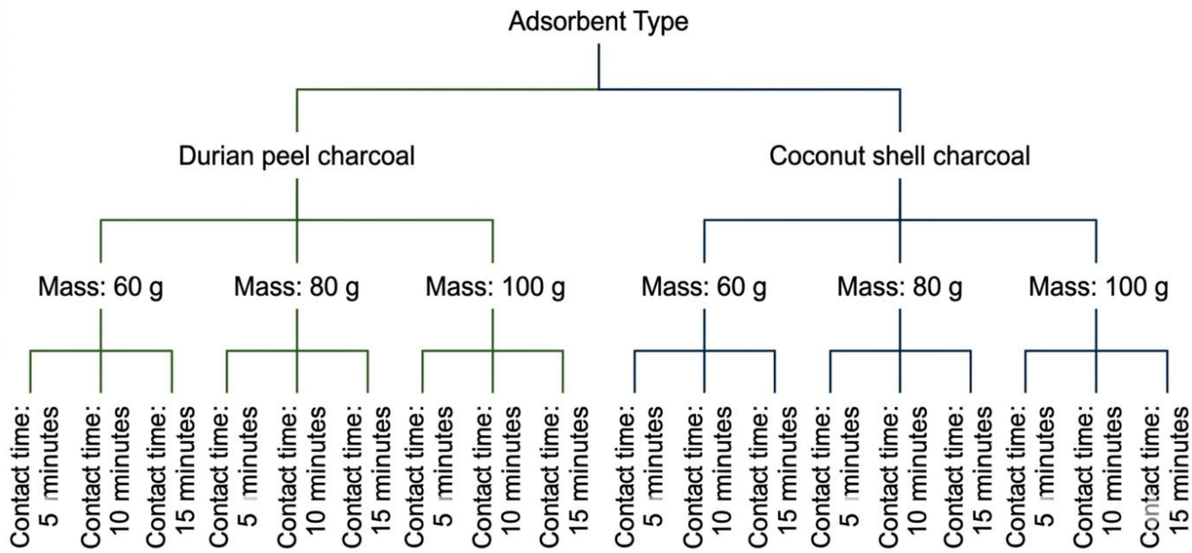

Diagram 1. Experimental Design Structure for Batch Adsorption Tests

Diagram 1 replaces the previous tabular presentation and illustrates the structured experimental matrix applied in the research. Each biofilter material was evaluated using three different adsorbent masses and three different contact times, resulting in nine treatment combinations per material. This configuration enabled systematic observation of how operational variables influenced $CaCO_3$ reduction.

Performance of Durian Peel Charcoal Biofilter

The first series of experiments examined the ability of durian peel charcoal (Durio zibethinus) to reduce $CaCO_3$ levels. Results demonstrated that this material was capable of substantially lowering hardness under all tested conditions. The most effective configuration was achieved with an adsorbent mass of 80 g and a contact time of 5 minutes, where post-treatment $CaCO_3$ concentrations were reduced to below the analytical detection limit.

Table 2. Optimal Outcome for Durian Peel Charcoal Biofilter

Initial $CaCO_3$ Concentration	Optimal Mass	Optimal Contact Time	Final $CaCO_3$ Result
568 mg/L	80 g	5 minutes	< detection limit

Table 2 summarises the best-performing condition identified for durian peel charcoal. The combination of moderate adsorbent mass and short exposure time produced rapid and highly effective removal of hardness-related ions. Increasing adsorbent mass beyond this point did not necessarily improve performance, indicating nonlinear adsorption behaviour.

The observed performance can be explained by the physicochemical characteristics of durian peel charcoal. High surface area and hierarchical porosity enhance access for Ca^{2+}, Mg^{2+}, and carbonate species (10). Surface functional groups such as carboxyl and phenolic moieties facilitate cation exchange and inner-sphere complexation with hardness ions (10,11). Although most published studies on durian peel charcoal focus on dyes and heavy metals, these mechanisms are applicable to hardness reduction. Activation processes and residual impregnation may further enhance affinity for divalent cations (21).

Performance of Coconut Shell Charcoal Biofilter

The second series of experiments evaluated coconut shell charcoal (Cocos nucifera) under identical operational conditions. This material also showed strong capacity to reduce $CaCO_3$ concentrations, although the optimal parameters differed from those observed for durian peel charcoal.

Table 3. Optimal Outcome for Coconut Shell Charcoal Biofilter

Initial $CaCO_3$ Concentration	Optimal Mass	Optimal Contact Time	Final $CaCO_3$ Result
568 mg/L	100 g	10 minutes	< detection limit

Table 3 indicates that coconut shell charcoal achieved maximum effectiveness at a higher mass and longer contact time compared with durian peel charcoal. These differences reflect variations in pore structure, surface chemistry, and adsorption kinetics between the two materials.

The effectiveness of coconut shell charcoal is consistent with its well-documented physical and chemical properties. Activated coconut-shell carbon typically exhibits high BET surface area and balanced micropore–mesopore structure, which enhance access for dissolved ions (22). Oxygen-containing surface functional groups promote ion exchange and complexation with divalent cations, supporting hardness removal (22). Although direct studies on $CaCO_3$ removal are limited, evidence from investigations on metal adsorption suggests strong potential for hardness control (23,24).

3.5 Comparative Performance of the Two Biofilter Media

A direct comparison of the two adsorbents highlights both their shared capabilities and their operational differences.

Table 4. Comparative Summary of Optimal Conditions for Both Biofilters

Biofilter Material	Optimal Mass	Optimal Contact Time	Performance Outcome
Durian peel charcoal	80 g	5 minutes	$CaCO_3$ reduced to < detection limit
Coconut shell charcoal	100 g	10 minutes	$CaCO_3$ reduced to < detection limit

Table 4 provides a consolidated comparison of the best-performing conditions for each material. Both biofilters were capable of reducing very high initial hardness to levels below detection limits, but the operational requirements differed. Durian peel charcoal exhibited faster kinetics, whereas coconut shell charcoal required greater mass and longer contact time to achieve comparable results.

Proper interpretation of these outcomes requires consideration of both percentage removal and absolute concentration changes, as well as clear documentation of influent levels and experimental design (14). The high initial $CaCO_3$ concentration in this study provided a stringent test environment that enabled meaningful differentiation between media performance.

Implications for Community-Scale Application in Palu

The experimental findings demonstrate that organic wastes readily available in Central Sulawesi can be transformed into effective biofilter media for household water treatment. The ability of both materials to achieve substantial $CaCO_3$ reduction within short contact times suggests strong potential for low-cost, decentralised applications suitable for communities in Palu City.

At the same time, the results emphasise the importance of context-specific optimisation. Initial contaminant concentration, adsorbent characteristics, and operational variables all shape treatment performance. As emphasised in adsorption literature, comparisons across studies are meaningful only when normalised to influent levels and supported by transparent experimental reporting (15).

Although the present research utilised batch experiments, the findings provide a foundation for future development of fixed-bed or household-scale filters. In column systems, parameters such as bed depth, residence time, and breakthrough behaviour would need to be evaluated to translate laboratory results into sustainable field applications (13).

Overall, the results confirm the technical feasibility of utilising organic-waste–based biofilters for $CaCO_3$ reduction and supply quantitative information necessary for subsequent optimisation and scale-up within the local context of Palu City.

DISCUSSION

The findings of this study provide important insights into the potential of organic-waste–based biofilters as alternative technologies for reducing calcium carbonate ($CaCO_3$) concentrations in household well water in Palu City, Central Sulawesi. The experimental results demonstrate that both durian peel charcoal and coconut shell charcoal are capable of substantially lowering hardness levels from an initially very high concentration. Nevertheless, the performance of these materials must be interpreted within the broader context of established hardness-removal technologies, adsorption theory, and the practical realities of community-scale water treatment.

From an efficiency perspective, conventional hardness-removal technologies such as lime–soda ash softening and ion exchange remain the most reliable and predictable methods available. These processes are supported by well-established kinetics, mature design standards, and extensive operational experience, enabling consistent removal of hardness across a wide range of water qualities (13–15). In contrast, the performance of organic-waste biofilters is inherently more variable and strongly dependent on factors such as feedwater chemistry, adsorbent preparation, and operational conditions. Studies have shown that agricultural-waste–derived adsorbents and biochars can achieve meaningful reductions of hardness-related species in controlled laboratory settings, yet their outcomes are often less predictable when applied to real groundwater matrices (17,19,23). Direct meta-analytic or side-by-side comparisons between organic adsorbents and conventional processes remain limited, which restricts the ability to make generalisable claims regarding relative efficiency (17–19).

Despite these limitations, the results of the present study illustrate several advantages of organic-waste biofilters in decentralised contexts. Both adsorbent media tested were able to reduce $CaCO_3$ concentrations to levels meeting or exceeding commonly accepted standards under optimised conditions. This outcome is particularly relevant for Palu City, where communities rely heavily on shallow wells with elevated hardness and where access to centralised treatment infrastructure is limited. In such settings, low-cost adsorbents derived from locally abundant wastes offer a practical and context-appropriate option. From a cost perspective, organic-waste adsorbents generally involve lower capital requirements and simpler operational demands compared with conventional softening systems, which typically require chemical inputs, energy, and skilled operators (17,19,24). However, potential savings must be weighed against issues of regeneration, media replacement, and long-term stability, which can increase lifecycle costs over time (17,19).

Hybrid treatment strategies may represent a realistic compromise between these two technological pathways. Integrating organic-waste biofilters as a pre-treatment stage before lime softening or ion exchange has been proposed as a means of reducing chemical demand and energy consumption while maintaining acceptable effluent quality (13,19). Such combined approaches could be particularly valuable in resource-limited communities like those in Palu, where gradual improvements to water treatment systems are more feasible than immediate adoption of fully engineered solutions.

The nonlinear relationships observed between biofilter mass, contact time, and removal efficiency in this study are consistent with established adsorption theory. Adsorption processes are inherently governed by coupled isotherm and kinetic phenomena. As adsorption sites become progressively occupied, capacity approaches saturation in a Langmuir-type manner, while reaction rates follow pseudo-second-order or intraparticle diffusion models (14,15,19). These dynamics explain why increases in adsorbent mass or contact time do not always produce proportional improvements in performance and why optimal conditions must be determined empirically. In fixed-bed or column systems, additional nonlinearities arise due to mass-transfer resistance and finite bed depth. Breakthrough models such as Thomas and Yoon–Nelson equations demonstrate that optimal residence time and bed configuration are necessary to achieve target effluent quality without excessive material use (13). Although the present research was limited to batch experiments, the trends observed suggest that similar considerations would apply if these materials were scaled to household filter designs. Furthermore, design-of-experiments approaches and response surface methodologies have been shown to reveal complex interactions among adsorbent dose, contact time, and initial concentration, enabling more precise identification of operating optima (15,16).

Mechanistic surface-chemistry models also help to explain the differing performances of the two adsorbents tested. The effectiveness of any organic adsorbent is strongly influenced by surface area, porosity, and the distribution of micro-, meso-, and macropores, which govern accessibility of hardness ions to active sites (22,25). Activation methods and chemical modifications alter pore structure and surface polarity, thereby affecting adsorption capacity (22,25). In addition, oxygen-containing functional groups such as carboxyl and carbonyl moieties enable ion exchange and complexation with Ca^{2+} and Mg^{2+} ions, while heteroatom doping can create specialised binding sites that further enhance hardness removal (22,25).

Differences between durian peel charcoal and coconut shell charcoal observed in this study are likely attributable to such physicochemical factors. Coconut shell charcoal is widely known for its high surface area and stable microporous structure, characteristics that favour adsorption of divalent cations. Durian peel charcoal, on the other hand, may possess a different balance of functional groups and pore characteristics, leading to faster initial uptake but greater sensitivity to operational conditions. Impregnation methods, such as phosphoric-acid treatment or sulfur doping, have been reported to modify surface acidity and create additional active sites, although the effects of such modifications can vary substantially among adsorbents (25). Regeneration capability and resistance to fouling are also critical determinants of long-term performance and lifecycle costs (22,26) however, these aspects were not investigated in the present study. This should therefore be acknowledged as a limitation, and future research should evaluate repeated use, regeneration performance, fouling behaviour, and long-term operation under continuous-flow or field conditions.

Another important consideration is compatibility with real feedwater conditions. Adsorbents that perform well in synthetic laboratory solutions may exhibit reduced capacity in natural groundwater due to competing ions, variable alkalinity, and fluctuating pH levels (22,27). The high initial $CaCO_3$ concentration in Palu groundwater provided a realistic and demanding test matrix, yet future studies should evaluate performance across a wider range of water qualities to ensure robustness. Such variability highlights the need for site-specific optimisation rather than universal design assumptions.

Although the experimental results are promising, several practical challenges must be acknowledged before household-scale biofiltration can be widely implemented. One major limitation is the inherent variability of feedwater chemistry, which can lead to inconsistent treatment outcomes and necessitate customised system design (27). Media fouling, biofilm formation, and gradual loss of adsorption capacity over time may require regular maintenance and regeneration procedures that are difficult to manage at the household level (27). Furthermore, the lack of standardised production methods and quality control for locally produced adsorbents can complicate reliability and user confidence (27).

Lifecycle considerations also play a crucial role in determining feasibility. While raw agricultural wastes are inexpensive and readily available in Central Sulawesi, costs associated with carbonisation, activation, transport, and eventual disposal or regeneration must be accounted for when evaluating scalability (22,26). In addition, regulatory and safety concerns extend beyond hardness removal alone. Household filters must also address potential microbial contamination and other chemical pollutants, requiring integrated treatment objectives and ongoing monitoring, which may be challenging without adequate training and institutional support (27).

Effective adoption of organic-waste biofilters therefore depends not only on technical performance but also on user education and operational simplicity. Designs must be robust, easy to maintain, and clearly understandable to prevent misuse or bypass behaviours (27). For communities in Palu City, programmes combining technical innovation with community training and local supply chains would be essential to translate laboratory success into sustainable public health benefits.

In summary, the present findings indicate that organic-waste–based biofilters represent a technically feasible and economically attractive option for hardness reduction in decentralised settings. While they are unlikely to replace conventional softening technologies in large-scale municipal systems, they offer valuable complementary or interim solutions for resource-constrained communities. Continued research integrating optimisation, regeneration studies, and pilot-scale testing in Palu and similar environments will be necessary to fully realise their practical potential.

CONCLUSION

This study investigated the effectiveness of two locally available organic-waste materials—durian peel charcoal and coconut shell charcoal—as biofilter media for reducing calcium carbonate ($CaCO_3$) concentrations in household well water in Palu City, Central Sulawesi, Indonesia. The findings demonstrate that both materials are technically capable of significantly lowering hardness levels from an initially very high baseline. Under optimised conditions, each adsorbent achieved reductions sufficient to meet acceptable drinking-water quality thresholds, confirming the practical feasibility of low-cost, decentralised treatment approaches in resource-limited settings.

The experimental results revealed that treatment performance was strongly influenced by operational parameters, particularly adsorbent mass and contact time. Optimal configurations differed between the two media, indicating that adsorption effectiveness is highly material-specific and nonlinear. Durian peel charcoal exhibited rapid initial adsorption kinetics and achieved its best performance at a relatively lower mass and shorter contact time, whereas coconut shell charcoal required greater mass and longer contact time to reach comparable results. These differences highlight the importance of empirical optimisation rather than uniform application of a single design assumption.

From a broader perspective, the study contributes to the growing body of evidence that organic-waste–based adsorbents can serve as viable alternatives or complements to conventional hardness-removal technologies. Although conventional methods such as ion exchange and lime–soda softening remain more predictable and scalable, they are often economically and technically inaccessible to many communities. The present research shows that locally sourced biofilters can provide meaningful improvements in water quality with minimal infrastructure and operational complexity, making them particularly suitable for decentralised household or community applications.

The study also advances understanding of the practical challenges associated with such approaches. The observed variability in performance across experimental conditions underscores the need for site-specific design, careful material preparation, and consideration of real groundwater characteristics. Issues of media regeneration, long-term durability, and user maintenance requirements must be addressed before large-scale implementation can be recommended. These considerations emphasise that technical effectiveness alone is insufficient; sustainable adoption requires integration with community education, supply chains, and simple operational protocols.

In terms of scientific contribution, this research provides comparative empirical data on two underexplored biofilter materials within a real groundwater matrix. Previous studies have largely focused on the use of agricultural wastes for removal of dyes or heavy metals, with limited attention to carbonate hardness. By directly comparing durian peel and coconut shell charcoal under identical conditions, the study offers new insights into their relative strengths, optimal operating parameters, and potential roles in household water treatment systems. The findings therefore extend existing knowledge on adsorption-based hardness control and demonstrate its applicability in the specific socio-environmental context of Palu City.

Several avenues for further research emerge from this work. Future studies should evaluate the long-term performance of these materials in fixed-bed or continuous-flow systems to better simulate household filtration scenarios. Investigation of regeneration techniques, fouling behaviour, and lifecycle costs is also necessary to determine practical sustainability. In addition, broader assessments across different groundwater sources in Central Sulawesi would help to clarify how variations in pH, alkalinity, and competing ions influence treatment outcomes. Integrating organic-waste biofilters with complementary treatment processes, such as disinfection or pre-filtration, may further enhance their utility for comprehensive water quality improvement.

Overall, the study confirms that transforming locally abundant organic wastes into functional biofilters represents a promising strategy for addressing persistent water hardness problems in decentralised settings. By demonstrating both technical feasibility and contextual relevance, the research provides a foundation for developing affordable, environmentally sustainable, and community-oriented solutions for safe water provision. The significance of this work lies not only in its experimental findings but also in its contribution to locally appropriate innovation for public health improvement in Palu City and comparable regions.

AUTHOR’S CONTRIBUTION STATEMENT

Hamidah: Conceptualization, Methodology, Investigation, Data Curation, Formal Analysis, Writing – Original Draft, Supervision, Project Administration.

Nur Rismawati: Methodology, Investigation, Validation, Data Curation, Writing – Review & Editing, Visualization.

CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this manuscript, the authors used Gemini, ChatGPT, DeepL, and Scite AI solely for grammar improvement, language refinement, sentence clarity, readability enhancement, and reference checking assistance. These tools were not used for data generation, analysis, or interpretation. All scientific interpretation, data analysis, conclusions, and final responsibility for the content of this manuscript remain entirely with the authors.

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