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Artículo original

# From Local Resources to Safe Water: Circular Approaches for Decentralized Water Treatment

*De los recursos locales al agua segura: enfoques circulares para el tratamiento descentralizado del agua*

https://doi.org/10.47606/ACVEN/PH0607

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**Recibido:** 12/08/2026 **Aceptado:** 22/10/2026

## ABSTRACT

Access to safe water remains a challenge in low-income and rural regions, where conventional purification can be unaffordable or unsustainable. Cocoa production waste, particularly cocoa pod husk, can be valorized as a precursor of activated carbon, while natural zeolites provide a complementary adsorptive and ion-exchange medium. This bibliometric review, complemented by a qualitative narrative synthesis, examines circular-economy strategies based on locally available adsorbent materials for decentralized water treatment. Bibliographic records were retrieved from Scopus using a structured search strategy and screened according to predefined eligibility criteria. A final corpus of 472 articles published between 2016 and 2026 was analyzed in VOSviewer using fractional counting and complementary Author Keywords and All Keywords co-occurrence networks. The reviewed evidence indicates complementary removal mechanisms and suggests that hybrid integration may improve efficiency, durability, and regeneration while valorizing agricultural residues and locally available minerals. The synthesis considers adsorption capacity, empty-bed contact time, removal targets, regeneration, and hydraulic performance. Important gaps remain regarding variable pH, competing ions, long-term stability, scale-up, reproducibility, and community adoption. The evidence supports a methodological pathway based on optimizing cocoa-residue activation, integrating the resulting carbon with zeolite media, and evaluating hybrid filters under realistic laboratory and field conditions. Within a circular-economy framework, this approach may contribute to locally grounded, low-cost drinking-water solutions for rural communities.

**Keywords:** cocoa pod husk; adsorption; natural zeolites; activated carbon; household filtration

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## RESUMEN

El acceso a agua segura continúa siendo un desafío en regiones rurales y de bajos ingresos, donde los sistemas convencionales de purificación pueden ser costosos o insostenibles. Los residuos de la producción de cacao, particularmente la cáscara de la mazorca, pueden valorizarse como precursores de carbón activado, mientras que las zeolitas naturales ofrecen mecanismos complementarios de adsorción e intercambio iónico. Esta revisión bibliométrica, complementada con una síntesis narrativa cualitativa, examina estrategias de economía circular basadas en adsorbentes disponibles localmente para el tratamiento descentralizado de agua. Los registros bibliográficos se obtuvieron de Scopus mediante una estrategia de búsqueda estructurada y se seleccionaron según criterios de elegibilidad predefinidos. Un corpus final de 472 artículos publicados entre 2016 y 2026 fue analizado en VOSviewer mediante conteo fraccional y redes complementarias de coocurrencia de Author Keywords y All Keywords. La evidencia muestra mecanismos de remoción complementarios y sugiere que la integración híbrida puede mejorar la eficiencia, durabilidad y regeneración, además de valorizar residuos agrícolas y minerales locales. La síntesis considera capacidad de adsorción, tiempo de contacto en lecho vacío, objetivos de remoción, regeneración y desempeño hidráulico. Persisten brechas relacionadas con pH variable, iones competidores, estabilidad a largo plazo, escalamiento, reproducibilidad y adopción comunitaria. La evidencia respalda una ruta metodológica orientada a optimizar la activación de residuos de cacao, integrar el carbón obtenido con zeolitas y evaluar filtros híbridos en condiciones realistas de laboratorio y campo. Este enfoque de economía circular puede contribuir a soluciones locales y de bajo costo para el abastecimiento de agua potable en comunidades rurales.

**Palabras Clave:** cáscara de cacao; adsorción; zeolitas naturales; carbón activado; filtración doméstica.

## INTRODUCTION

Access to safely managed drinking water remains uneven worldwide. In 2022, 73% of the global population used safely managed drinking-water services, and current progress remains insufficient to ensure universal access by 2030 (United Nations Children's Fund & World Health Organization, 2023; UN-Water, 2023). In Latin America, water security remains constrained by infrastructure, governance, and geographic challenges (World Bank, 2023). Evidence from rural communities in other developing regions further highlights the importance of water-supply infrastructure for improving household welfare and supporting local livelihoods (Magbondé et al., 2024). In Ecuador, access to drinking water is recognized as a fundamental right, although economic and institutional challenges may affect its effective realization, particularly among vulnerable households (Martínez Moscoso et al., 2018).

Decentralized treatment has therefore gained attention as a complement to centralized infrastructure. Low-cost filters based on locally available materials offer potential solutions for decentralized water treatment, particularly where access to conventional infrastructure is limited (Ciawi & Khoiruddin, 2024; Nidheesh et al., 2024). More broadly, decentralized water-management systems have demonstrated potential to improve resource efficiency and resilience, although their performance depends on the scale and context of implementation (Garrido-Baserba et al., 2024). Circular-economy approaches promote resource recovery, waste reduction, and water resilience, providing a broader

sustainability framework for the valorization of locally generated residues into water-treatment materials (Organisation for Economic Co-operation and Development, 2025; World Bank Water Practice, 2024). Agricultural residues are particularly relevant because they can be valorized into carbon-based adsorbents for water treatment, providing an alternative pathway for biomass utilization (Aguilar-Rosero et al., 2022; Koul et al., 2022).

Ecuador is a major cocoa-producing country, making cocoa pod husk a potentially significant source of agricultural biomass (International Cocoa Organization, n.d.). Owing to its lignocellulosic composition, this residue has been investigated as a precursor for activated carbon production and other value-added applications (Cruz et al., 2012; de Souza Vandenberghe et al., 2022). Natural zeolites provide a complementary material because their aluminosilicate frameworks offer cation exchange, molecular sieving, and adsorption functions (Kumari et al., 2024; Morante-Carballo et al., 2021). Studies on zeolite-based composites suggest that combining zeolites with complementary adsorbent materials can enhance contaminant-specific removal under suitable conditions (Roshanfekr Rad & Anbia, 2021). More specifically, zeolite–cocoa-shell activated charcoal systems have demonstrated potential for ammonium removal from greywater (Susilawati et al., 2023).

Accordingly, this review asks: how can natural zeolites and cocoa-pod-husk activated carbon be optimized to develop household water filters for rural communities?

## METHODOLOGY

This study employed a bibliometric review complemented by a qualitative narrative synthesis to characterize the conceptual structure of the scientific literature related to zeolites, adsorption, circular-economy strategies, waste valorization, and water-treatment applications. Bibliometric analysis was selected because it enables the identification of dominant research themes, relationships among scientific concepts, emerging topics, and comparatively underrepresented areas through keyword co-occurrence analysis. The bibliometric component was complemented by a qualitative interpretation of the retrieved literature. This combination allowed the study not only to quantify the thematic organization of the field but also to identify conceptual gaps relevant to the integration of locally available materials, biomass-derived adsorbents, circular-economy strategies, and decentralized water-treatment applications. The analysis was conducted using bibliographic records retrieved from Scopus and processed with VOSviewer. Two complementary keyword networks were evaluated using the fractional counting method: one based exclusively on Author Keywords and another based on All Keywords, which incorporated both author-defined and indexed terminology. The comparison of both networks was used to distinguish explicitly stated research priorities from the broader conceptual structure of the indexed literature.

The bibliographic information used in this review was obtained from the Scopus database. Scopus was selected because of its multidisciplinary coverage of peer-reviewed literature in environmental sciences, materials science, chemical engineering, sustainability, waste management, adsorption processes, and water-treatment technologies. The bibliographic records were exported in CSV format and prepared for processing in VOSviewer. The exported information included, where available, authors, publication year, title, abstract, author keywords, index keywords, source title, DOI, affiliations, references, and document type. The final cleaned database used for the bibliometric analysis contained 472 scientific articles published in English between 2016 and 2026. Duplicate verification was performed using document title, DOI, and Scopus EID. No duplicated records were

identified in the cleaned dataset; therefore, the 472 records were retained for bibliometric mapping.

The search strategy combined concepts related to zeolitic materials, circular economy, resource recovery, waste valorization, sustainability, and environmental applications. Search terms were applied to the title, abstract, and keyword fields in Scopus using Boolean operators. The search structure followed the combination of material-related and circular-economy-related concepts, using terms such as:

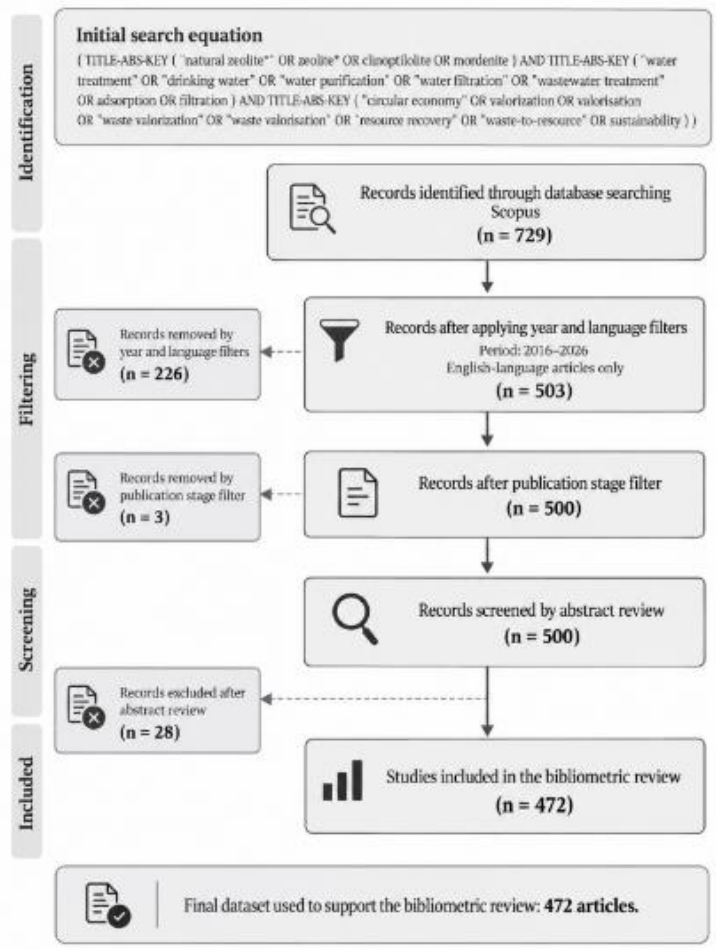
*( TITLE-ABS-KEY ( "natural zeolite*" OR zeolite* OR clinoptilolite OR mordenite ) AND TITLE-ABS-KEY ( "water treatment" OR "drinking water" OR "water purification" OR "water filtration" OR "wastewater treatment" OR adsorption OR filtration ) AND TITLE-ABS-KEY ( "circular economy" OR valorization OR valorisation OR "waste valorization" OR "waste valorisation" OR "resource recovery" OR "waste-to-resource" OR sustainability ) )*

The retrieved results were subsequently restricted according to document type, language, and the temporal range established for the bibliometric analysis. Only research articles written in English were retained. Before network construction, the Scopus database was cleaned and standardized for VOSviewer analysis. Particular attention was paid to keyword consistency because bibliographic databases frequently contain singular and plural forms, spelling variants, alternative terminology, and synonymous expressions that can artificially fragment bibliometric networks. For this purpose, a customized VOSviewer thesaurus file was developed. The database contained approximately 5,569 unique keyword and index-term forms, from which 163 thesaurus rules were generated and validated. These rules were used either to merge equivalent terms or to exclude generic indexing expressions that did not contribute to the thematic interpretation of the network.

Studies were considered eligible when they consisted of peer-reviewed research articles indexed in Scopus, were published in English, fell within the temporal range established for the bibliometric database, and addressed topics related to zeolites, adsorption, circular-economy principles, waste valorization, resource recovery, sustainability, water treatment, wastewater treatment, or related environmental applications. In addition, records were required to contain sufficient bibliographic information to support bibliometric analysis. Studies were excluded when they corresponded to document types other than research articles, were published in languages other than English, lacked sufficient bibliographic information for analysis, or fell outside the thematic and temporal scope defined for the review. After application of these criteria and database cleaning, the final dataset used in VOSviewer comprised 472 documents, all of which were classified as research articles and published in English. Earlier foundational studies published outside the bibliometric time window were retained only for mechanistic, historical, and contextual interpretation and were not included in the VOSviewer corpus.

The records retrieved from Scopus were screened according to the predefined eligibility criteria and subsequently checked for bibliographic consistency and duplicate entries using title, DOI, and Scopus EID. The retained records were then standardized through a customized thesaurus to harmonize synonymous terms and spelling variants before being imported into VOSviewer for fractional-counting co-occurrence analysis.

**Figure 1.**
*PRISMA flow diagram for the bibliometric review*




Bibliographic records were analyzed in VOSviewer through keyword co-occurrence mapping. Two complementary networks were constructed using Author Keywords and All Keywords to capture, respectively, author-defined research themes and the broader conceptual structure derived from database indexing. The fractional counting method was applied to normalize the contribution of individual publications and reduce the disproportionate influence of records containing a large number of keywords. Network interpretation considered term occurrence, link strength, proximity, and cluster membership. The two maps were examined comparatively to identify dominant thematic structures, conceptual interconnections, and weakly represented or weakly connected research areas. Bibliometric patterns were subsequently integrated with the qualitative synthesis of the selected literature to support the identification of research gaps relevant to circular, resource-efficient, and decentralized water-treatment approaches.

The qualitative synthesis was developed through an expert-informed purposive selection of scientific publications based on the authors' prior knowledge of the research field. Unlike the systematically delimited bibliometric corpus, this component did not involve an independent exhaustive database search or a separate PRISMA-based screening procedure. Instead, previously identified publications were selected according to their

relevance to the scientific foundations, technical mechanisms, operational limitations, and practical applications examined in the review.

The selected literature included foundational studies, experimental investigations, review articles, and contextual sources addressing natural zeolites, biomass-derived activated carbon, hybrid adsorbent systems, and decentralized water treatment. The evidence was organized into five thematic dimensions: (i) cocoa-residue valorization and activated-carbon production; (ii) physicochemical properties and ion-exchange mechanisms of natural zeolites; (iii) contaminant-removal applications of zeolite–carbon systems; (iv) operational performance, hydraulic behavior, and regeneration; and (v) circular-economy implications and community-level adoption.

The qualitative synthesis and the bibliometric analysis were treated as methodologically distinct components. While the bibliometric analysis was based on the predefined Scopus dataset of 472 articles, the qualitative synthesis drew on purposefully selected publications to provide mechanistic, technical, historical, and contextual interpretation. The distinction between these components was based on their selection procedures and analytical purposes, rather than on an assumption that their bibliographic sources were mutually exclusive. Foundational publications predating the bibliometric period were retained where relevant to explaining established adsorption mechanisms and material properties. The qualitative component therefore provided a focused narrative interpretation rather than an exhaustive or independently systematic synthesis of treatment effectiveness. Its integration with the bibliometric findings was intended to contextualize research trends, identify technical limitations, and formulate research priorities. Potential limitations associated with expert-informed selection, including selection bias and incomplete literature coverage, were acknowledged when interpreting the findings (Snyder, 2019).

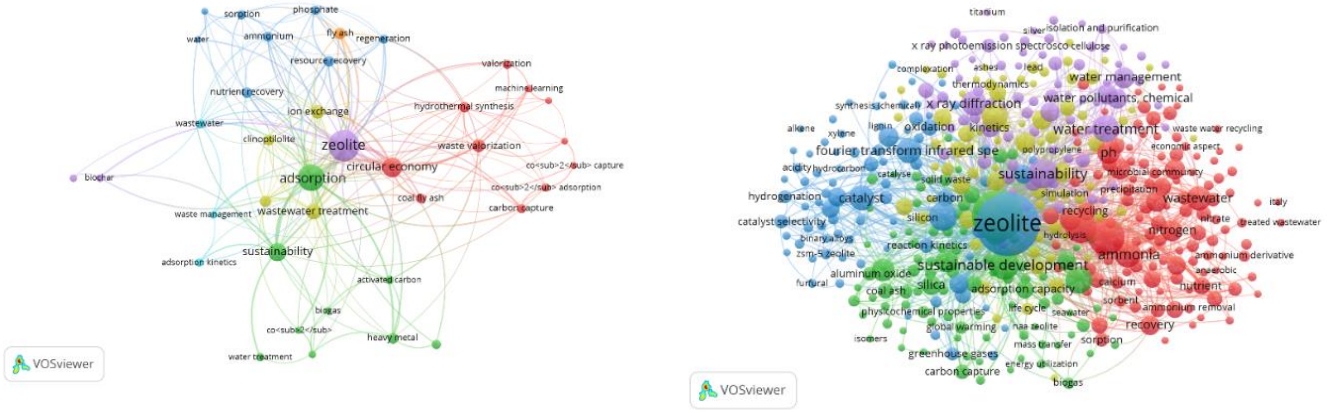
Methodological rigor was addressed through a structured and reproducible review process, including predefined eligibility criteria, bibliographic verification, duplicate screening, standardized keyword normalization, and consistent application of the same counting method across all network analyses. These procedures were intended to reduce selection, duplication, and terminological biases that could affect the interpretation of bibliometric patterns. Because the study combined systematic literature screening with bibliometric mapping rather than effect-size estimation, no conventional intervention-specific risk-of-bias tool was applied. Instead, methodological quality was considered in relation to the transparency, completeness, and consistency of the bibliographic records included in the synthesis. Potential sources of bias include the exclusive use of Scopus, differences in author-assigned and indexed terminology, and the sensitivity of network structures to keyword selection and normalization. Accordingly, low-frequency or weakly connected terms were interpreted as indicators of limited thematic consolidation rather than as evidence of an absence of research. The expert-informed purposive selection of publications for the qualitative synthesis may introduce selection bias and does not guarantee exhaustive coverage of the available evidence. Therefore, the qualitative findings were interpreted as contextual and technical insights rather than as the results of an independently systematic assessment of treatment effectiveness (Snyder, 2019).

## RESULTS

Keyword co-occurrence analysis revealed a multidimensional research structure connecting adsorbent materials, circular-economy strategies, resource recovery, and water-treatment applications. The Author Keywords network (Figure 2a) showed a central thematic structure dominated by zeolite, adsorption, circular economy, wastewater treatment,

sustainability, ion exchange, and waste valorization. Their central positions and interconnections indicate that material performance, contaminant removal, and resource circularity represent established research domains.

**Figure 2.**
Keyword co-occurrence networks generated in VOSviewer using fractional counting: (a) Author Keywords and (b) All Keywords.




(a) (b)

The All Keywords network (Figure 2b) provided a broader representation of the field by incorporating indexed terminology. In addition to the central role of zeolite, the network emphasized water and wastewater treatment, adsorption capacity, nitrogen and ammonium removal, material characterization, catalysis, sustainability, and resource recovery. The higher density of this network reflects the wider conceptual vocabulary generated by database indexing, whereas the Author Keywords network more directly captures the research priorities explicitly defined by authors.

Comparative examination of both networks suggests that the literature is well consolidated around zeolites, adsorption mechanisms, wastewater treatment, and resource recovery, whereas the integration of these themes with locally sourced biomass-derived adsorbents and decentralized drinking-water applications is less prominent. In particular, concepts related to cocoa residues, cocoa-derived activated carbon, household filtration, point-of-use treatment, and rural water systems do not emerge as dominant thematic nodes. This pattern should not be interpreted as evidence of an absence of research, but rather as an indication of comparatively limited thematic consolidation. These weakly represented intersections provide the rationale for examining how locally available mineral and biomass resources can be integrated within circular and decentralized water-treatment strategies.

**Agricultural residues and cocoa-pod-husk valorization**

Agricultural production generates substantial quantities of residual biomass, including husks, stems, leaves, and other lignocellulosic by-products. Their management represents both an environmental challenge and an opportunity for resource recovery. Although agricultural residues may serve alternative purposes such as soil amendment,

composting, and animal feeding, poorly managed fractions can contribute to local environmental pressures. Their conversion into carbonaceous adsorbents offers a potential circular-economy pathway, provided that material recovery, processing requirements, and environmental trade-offs are appropriately considered (Koul et al., 2022; Patel & Panwar, 2023). Cocoa pod husk is particularly relevant in cocoa-producing regions such as Ecuador because it represents a substantial biomass stream generated during fruit processing. The amount of recoverable residue depends on production volume, fruit composition, moisture content, and existing uses; therefore, national residue availability cannot be established reliably from cocoa bean production statistics alone. Nevertheless, the lignocellulosic characteristics of cocoa pod husk make it a promising precursor for carbon-based adsorbents (de Souza Vandenberghe et al., 2022).

Experimental evidence supports its technical potential for activated-carbon production. Cruz et al. (2012) investigated cocoa-pod-husk-derived activated carbons using different precursor particle sizes, chemical activating agents ($K_2CO_3$, KOH, and $ZnCl_2$), and carbonization temperatures of 500, 650, and 800 °C under a nitrogen atmosphere. The resulting materials were evaluated through surface-area, pore-structure, and yield measurements, demonstrating the importance of processing conditions in determining adsorbent characteristics. However, the production and characterization of activated carbon should not be interpreted as direct evidence of its effectiveness in household drinking-water treatment, which requires contaminant-specific adsorption and filtration experiments. From a circular-economy perspective, the environmental viability of cocoa-pod-husk-derived activated carbon depends on the combined effects of biomass recovery, carbonization energy, chemical activation, washing-water consumption, product yield, media regeneration, and end-of-life management.

Consequently, future assessments of cocoa-pod-husk-derived activated carbon should consider both adsorbent performance and the environmental burdens associated with its production and use. Although life-cycle assessment studies of agricultural-residue-derived biochar provide a relevant methodological basis, the environmental benefits of cocoa-pod-husk activated carbon for water treatment remain to be demonstrated through application-specific evaluation (Patel & Panwar, 2023).

**Natural zeolites as filtration media**.

Natural zeolites are crystalline, hydrated aluminosilicates characterized by three-dimensional frameworks containing interconnected channels, exchangeable cations, and water molecules. Their ion-exchange and adsorption properties support applications in water and wastewater treatment, particularly for ammonium and selected metal ions. However, contaminant-removal performance depends on zeolite mineralogy, exchangeable-cation composition, particle size, pretreatment, and solution chemistry. Competition among dissolved ions and differences in operating conditions can further influence adsorption behavior and effective treatment capacity (Hedström, 2001; Pérez-Botella et al., 2022; Wang & Peng, 2010). The availability of natural zeolitic deposits in Ecuador provides a geological basis for investigating locally sourced filtration media. Machiels et al. (2008) characterized zeolite-bearing rocks from the Cayo Formation near Guayaquil and identified calcium-rich heulandite and clinoptilolite as predominant zeolitic phases, with less abundant laumontite, mordenite, and analcime. The reported zeolite content ranged approximately from 10% to 60% in the investigated rocks, demonstrating substantial mineralogical variability. These results establish the presence of zeolitic resources but do not, by themselves, demonstrate suitability for drinking-water treatment. Consequently, the selection of Ecuadorian natural zeolites for decentralized filtration should

be preceded by mineralogical and physicochemical characterization, including phase composition, exchange capacity, particle-size distribution, and potentially releasable constituents. Such characterization is necessary to distinguish geological availability from actual adsorbent performance and to determine whether the material can be incorporated into a reproducible treatment medium.

**Hybrid zeolite-activated carbon systems**

The integration of natural zeolites and activated carbon is supported by their complementary physicochemical properties, particularly the ion-exchange capacity of zeolites and the adsorption affinity of activated carbon for various organic contaminants. However, the effectiveness of hybrid configurations depends on the specific adsorbent composition, target pollutants, water matrix, and operating conditions. Experimental studies have demonstrated the contaminant-specific adsorption potential of combined zeolite–carbon materials under different treatment conditions, although their effectiveness depends on the adsorbent formulation and the characteristics of the treated water.

Halim et al. (2010) reported higher ammoniacal nitrogen adsorption capacity for a multicomponent zeolite–activated carbon-based adsorbent than for the individual zeolite and activated carbon materials in landfill leachate treatment. More directly related to cocoa-derived adsorbents, Susilawati et al. (2023) developed a zeolite–activated charcoal filter prepared from cocoa shells for ammonium removal from greywater, reporting a removal efficiency of 68.25% for a zeolite-to-carbon ratio of 75:25 after 1 h of contact under the investigated experimental conditions. These results support the potential of hybrid materials, although their applicability to drinking-water treatment requires separate validation.

Additional studies illustrate the diversity of applications and the limitations of direct extrapolation. Susilawati et al. (2022) investigated a zeolite–cocoa-shell activated charcoal nanofilter for bioethanol purification, rather than contaminant removal from drinking water. Susilawati et al. (2024) examined cocoa-shell activated charcoal combined with natural zeolite for iron and manganese adsorption in well water. At the pilot scale, Wan et al. (2021) evaluated a combined adsorption system consisting of separate granular activated-carbon and zeolite columns connected in series for removing hazardous trace elements from coal-gasification wastewater. Although these studies demonstrate relevant material properties and treatment mechanisms, differences in feedwater composition, adsorbent characteristics, and treatment objectives prevent their results from being directly generalized to household drinking-water applications. Consequently, the available evidence provides a technical rationale for investigating hybrid zeolite–cocoa-derived carbon filters, but does not establish their effectiveness, operational durability, or drinking-water safety under rural household conditions. Further research should examine contaminant-specific removal, competing ions, hydraulic performance, media regeneration, and microbiological quality using representative source waters.

**Table 1.**

*Comparative parameters of natural zeolites and cocoa-pod-husk activated carbon for water treatment*

| Parameter | Natural Zeolites (clinoptilolite, mordenite) | Cocoa pod husk–based Activated Carbon | References |
|---|---|---|---|
| Typical adsorption capacity | Contaminant-specific; ammonium and selected metal-ion uptake depend on mineralogy, pretreatment, | Contaminant-specific; capacity depends on carbonization, activation, surface chemistry, | (Hedström, 2001; Jjagwe et al., 2021; Wang & Peng, 2010) |

| | | | |
|---|---|---|---|
| | competing ions, and solution conditions. | porosity, and target pollutants. | |
| Dominant mechanism | Cation exchange, adsorption, and molecular-sieving effects, depending on the target species. | Adsorption associated with pore structure and surface functional groups; mechanisms vary with pollutant chemistry. | (Jjagwe et al., 2021; Wang & Peng, 2010) |
| Empty-bed contact time (EBCT) | Must be established for the selected zeolite, bed configuration, flow rate, and target contaminant. | Must be determined for the prepared carbon and actual column conditions; no universal EBCT can be assigned. | (Hedström, 2001; Jjagwe et al., 2021) |
| Filtration rate | Hydraulic filtration rate depends on bed configuration, particle-size distribution, applied flow rate, and operating conditions; it must be established experimentally. | Influenced by particle-size distribution, packing density, mechanical stability, and pressure loss. | (Hedström, 2001; Jjagwe et al., 2021) |
| Regeneration | Chemical or biological regeneration may be applicable to ammonium-loaded zeolites; effectiveness depends on the regeneration method and operating conditions. | Regeneration potential depends on the carbon properties, adsorbed contaminants, and selected regeneration method; performance across cycles requires experimental validation. | (Hedström, 2001; Jjagwe et al., 2021) |
| Availability (Ecuador case) | Natural deposits documented in coastal Ecuador, particularly the Cayo Formation; mineral quality varies. | Cocoa pod husk is a potentially local precursor; annual residue tonnage is not established by the cited sources. | (de Souza Vandenberghe et al., 2022; Machiels et al., 2008; Morante Carballo, 2004) |

**Note.* Adsorption capacities and operating parameters depend on the contaminant, material properties, and operating conditions; therefore, they should not be interpreted as universal design specifications. Empty-bed contact time (EBCT), calculated as empty-bed volume divided by volumetric flow rate, and filtration rate require experimental determination for each filter configuration. Comparisons across studies must consider differences in water matrices, adsorbent properties, and testing methods. Local resource availability does not guarantee material suitability or drinking-water safety. This qualitative comparison synthesizes published evidence and does not represent a direct experimental evaluation of Ecuadorian natural zeolites and cocoa-pod-husk-derived activated carbon.*

The parameters summarized in Table 1 highlight the complementary characteristics of natural zeolites and cocoa-derived activated carbon, while emphasizing the importance of material-specific testing. Experimental evidence for combined systems has been reported by Susilawati et al. (2023), who investigated zeolite–cocoa-shell activated charcoal filters for ammonium removal from greywater. Their study identified differences in filter characteristics associated with composition and sintering conditions. Nevertheless, the reported performance is specific to the investigated material and wastewater matrix and cannot be generalized to rural drinking-water treatment without additional experimental validation.

**Rural applications and knowledge gaps**

For rural Ecuador, the integration of locally generated agricultural residues and natural mineral resources represents a potential pathway toward decentralized water

treatment. Experimental investigations combining zeolite and activated carbon have demonstrated relevant adsorption mechanisms in different water matrices, although their direct application to household drinking-water treatment remains insufficiently validated (Halim et al., 2010; Susilawati et al., 2023; Wan et al., 2021). Beyond treatment performance, household adoption depends on filter design, ease of assembly, compatibility with domestic spaces, and access to replacement components. Wainaina et al. (2023), in a study involving households in northern Kenya, identified practical usability and filter configuration as important determinants of consistent use. These findings highlight the need to evaluate technical performance and user-related factors together when developing decentralized filtration systems.

From a community-adoption perspective, adsorption capacity and hydraulic performance must be considered alongside the affordability of replacement media, the time required for routine maintenance, and the availability of local technical support. These factors should be evaluated with prospective users rather than inferred from laboratory performance alone. The evidence on household-filter use indicates that sustained operation depends not only on technical effectiveness but also on practical conditions of use (Wainaina et al., 2023).

The literature therefore identifies a clear lab-to-field gap. Future studies should compare activation routes for cocoa pod husk, establish the effect of zeolite-to-carbon ratio and particle size, quantify pressure drop and empty-bed contact time, evaluate breakthrough under mixed contaminants, and measure performance after repeated regeneration. Scale-up should also account for the compositional variability and purity of natural zeolite deposits, which may influence material consistency and reproducibility, as documented for natural zeolites in adsorption applications (Ackley et al., 2003). Additionally, variability in cocoa residues, production costs, logistics, and quality control should be considered, particularly because activated carbon production economics depend on feedstock characteristics, product yield, and activation conditions (Stavropoulos & Zabaniotou, 2009).

## DISCUSSION

The bibliometric findings complement the qualitative synthesis by identifying established research domains associated with zeolites, adsorption, wastewater treatment, and resource recovery, while indicating comparatively limited thematic integration with cocoa-derived carbon and decentralized household water treatment within the selected Scopus corpus. This pattern must be interpreted in relation to the search strategy and keyword-based analysis rather than as evidence of an overall absence of relevant research. The qualitative literature provides a technical basis for investigating hybrid filtration media because natural zeolites exhibit ion-exchange properties relevant to ammonium and selected metal ions, whereas activated carbon can adsorb different classes of organic contaminants, depending on its surface chemistry and pore structure (Hedström, 2001; Jjagwe et al., 2021; Wang & Peng, 2010). Experimental investigations involving combined zeolite and activated-carbon materials have demonstrated treatment potential in landfill leachate, greywater, and industrial wastewater applications (Halim et al., 2010; Susilawati et al., 2023; Wan et al., 2021). However, these findings are matrix-specific and cannot establish equivalent performance in rural drinking-water sources without contaminant-specific validation and assessment of operating conditions. Therefore, the proposed zeolite–cocoa-derived carbon configuration should be regarded as a research-supported concept requiring further experimental development rather than as an already validated household drinking-water technology.

The circular-economy argument is equally important. Converting cocoa pod husk into activated carbon can transform a locally abundant residue into a treatment input, potentially reducing waste while creating local value. Nevertheless, this benefit depends on how the carbon is produced. High temperatures, activating chemicals, extensive washing, low yields, or difficult regeneration can shift environmental and economic burdens rather than eliminate them (Patel & Panwar, 2023; Stavropoulos & Zabaniotou, 2009). For that reason, future studies should evaluate not only adsorption capacity but also mass yield, energy and chemical use, water demand during washing, regeneration, end-of-life options, and cost per volume of treated water.

A second limitation is external validity. Much of the evidence is based on controlled laboratory solutions, whereas rural source waters contain variable pH, hardness, dissolved organic matter, suspended solids, microorganisms, and competing ions. Pilot testing should therefore use representative local waters and report hydraulic as well as adsorption performance. Household-level usability and social acceptance are also important: difficulties in filter assembly, limited access to spare parts, poor fit within domestic spaces, and uncertainty about proper operation may discourage consistent use (Wainaina et al., 2023). These technical and social dimensions should be evaluated together before scaling the approach.

For future rural pilots, technical indicators (contaminant-specific removal, flow stability, media lifetime, and regeneration performance) should therefore be assessed together with user-centred indicators, including perceived ease of use, maintenance burden, willingness and ability to replace media, and continuity of use. Participatory feedback could help identify design changes before wider deployment. Furthermore, adsorption performance alone cannot establish drinking-water safety: microbiological quality and compliance with applicable drinking-water standards must be independently verified before recommending household consumption.

**Technical performance and implications for community adoption**

The translation of hybrid zeolite–cocoa-derived carbon filters into household applications requires linking technical performance with the practical conditions that determine sustained use. Adsorption capacity and contaminant-removal efficiency influence the potential effectiveness and replacement frequency of filtration media, whereas hydraulic performance, empty-bed contact time, and head loss affect water production rates and the time households must devote to treatment. Similarly, regeneration efficiency, material durability, and the availability of replacement media influence maintenance requirements and recurring costs. These relationships should be evaluated in the context of household water demand, locally available resources, and users' capacity to operate and maintain the proposed treatment system. Empirical evidence supports the importance of considering usability alongside treatment performance. Wainaina et al. (2023), in a study of household water filters during a prolonged drought in northern Kenya, identified filter compatibility with household space, spare-part availability, assembly requirements, and users' understanding of filter operation as factors associated with consistent use. Although these findings concern different filtration technologies and cannot be directly generalized to zeolite–cocoa-carbon systems, they demonstrate why technically promising devices may face practical barriers to sustained adoption.

For future rural applications in Ecuador, the proposed hybrid-filter concept should therefore be evaluated through an integrated technical and user-centred framework. Technical monitoring should include contaminant-specific removal, treated-water flow rate, hydraulic stability, media lifetime, and maintenance frequency. Complementary household-

level assessments should examine ease of installation and cleaning, affordability of replacement materials, perceived water quality, user understanding, and continuity of use. Participatory pilot testing could help identify modifications needed to align filtration performance with household practices and local resource constraints. Importantly, community acceptance and adsorption performance alone cannot establish drinking-water safety; microbiological and physicochemical compliance must be independently verified before household consumption is recommended.

## CONCLUSIONS

The bibliometric analysis revealed a well-established research base around zeolites, adsorption, and wastewater treatment, but comparatively weaker integration with agricultural-waste valorization and decentralized drinking-water applications. Natural zeolites and cocoa-pod-husk activated carbon have complementary properties that justify further investigation as a hybrid medium for decentralized drinking-water treatment. The approach is consistent with circular-economy objectives because it can valorize an abundant agricultural residue while taking advantage of locally available mineral resources. The main evidence gaps concern standardized activation, material ratios, hydraulic behavior, mixed-contaminant performance, regeneration, long-term stability, reproducibility, cost, and community adoption. Progress toward household application therefore requires controlled comparative experiments followed by pilot tests with representative rural waters and explicit assessment of both technical performance and practical usability.

Accordingly, future validation should integrate water-quality outcomes with household usability and community participation, so that technical feasibility is not mistaken for demonstrated acceptance or safe, sustained adoption.

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