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Systematic Review

Zeolites and Activated Carbons in Hydroponics: A Systematic Review of Mechanisms, Performance Metrics, Techno-Economic Analysis and Life-Cycle Assessment

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Abstract

The sustainable operation of hydroponic systems depends on maintaining the chemical stability of circulating nutrient solutions and preventing the accumulation of toxic compounds. The accumulation of phytotoxic ammonium, heavy metals, and organic metabolites in recirculating nutrient solutions remains one of the key challenges limiting the efficiency, sustainability, and scalability of hydroponic cultivation. This review provides a comprehensive comparative analysis of zeolites, activated carbons (ACs), and their functionalized and composite forms as key sorbents for nutrient management, contaminant removal, and environmental safety in hydroponic cultivation. Natural zeolites, with their well-defined crystalline structure and high ion-exchange selectivity toward ammonium and heavy metal cations, enable effective NH_4^+/K^+ balance regulation and phytotoxicity mitigation. ACs, characterized by high specific surface area and tunable surface chemistry, complement zeolites by offering extensive adsorption capacity for organic compounds, root exudates, and pesticide residues, thereby extending the operational lifespan of nutrient solutions and improving overall system performance. Further advancements include the integration of zeolites and ACs with two-dimensional (graphene, g-C_3N_4) and three-dimensional (MOF, COF) frameworks, yielding multifunctional materials that combine adsorption, ion exchange, photocatalysis, and nutrient regulation. Transition-metal modification, particularly with Fe, Mn, Cu, Ni, and Co, introduces redox-active centers that enhance sorption, catalysis, and phosphate stabilization. The comparative synthesis reveals that the combined application of zeolite- and carbon-based composites offers a synergistic strategy for developing adaptive and low-waste hydroponic systems. From a techno-economic and environmental standpoint, the judicious application of these materials paves the way for

more resilient, efficient, and circular hydroponic systems, reducing fertilizer and water consumption, lowering contaminant discharge, and enhancing food security. This systematic review was conducted according to the PRISMA 2020 guidelines. Relevant studies were identified through Scopus, Web of Science, and Google Scholar databases using specific inclusion and exclusion criteria.

Keywords: zeolites; activated carbon; hydroponic systems; 2D/3D composites; transition-metal functionalization; sorption and catalysis

1. Introduction

Hydroponics is a technology for growing plants without the use of soil, in which the root system is immersed in a nutrient solution of strictly controlled composition. This approach ensures higher yields and accelerated plant growth by optimizing the supply of macro- and microelements. Unlike traditional agriculture, hydroponic systems make it possible to reduce water consumption by 70–90%, minimize fertilizer losses, and decrease the carbon footprint of production [1].

The advantages of hydroponics are manifested in the possibility of year-round cultivation, efficient use of enclosed spaces, and integration into urban ecosystems, including vertical farms and green building systems (Figure 1). Recent studies demonstrate that such systems can simultaneously serve as wastewater treatment and biofiltration units, making them promising components of the circular economy [2].

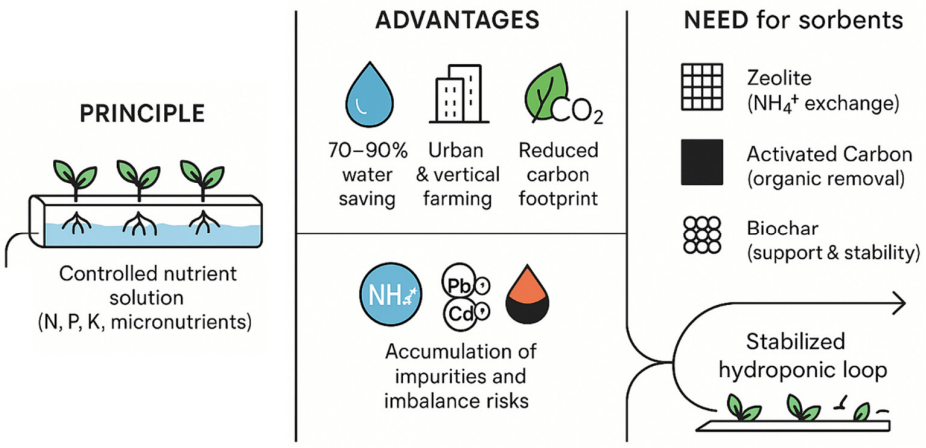


Figure 1. Principles, Advantages, and Challenges of Hydroponics.

Despite its numerous advantages, hydroponic technology faces several challenges. Among them are the need for strict control of nutrient solution quality, prevention of the accumulation of undesirable impurities (ammonium, heavy metals, organic metabolites), and ensuring substrate stability for long-term use. In this regard, increasing attention is being paid to the application of natural and modified sorbents, including zeolites, ACs, and biochar, which can enhance moisture retention, bind toxic compounds, and stabilize the chemical composition of nutrient solutions [3,4].

1.1. The Relevance of the Use of Sorbents in Hydroponic Systems

One of the key factors determining the stability of hydroponic systems is maintaining the chemical composition of the nutrient solution within the optimal range for plant growth. During intensive solution circulation, undesirable compounds—such as ammonium ions, heavy metals, organic metabolites, and secondary microbial products—tend to accumulate,

which may cause phytotoxicity and reduce crop productivity. Consequently, increasing attention has been directed toward the use of sorbent materials capable of regulating the solution composition without disrupting the balance of macro- and microelements [5].

Natural zeolites are considered among the most effective materials due to their high ion-exchange capacity and selectivity toward ammonium ions. A number of studies have shown that incorporating zeolites into substrates or using them in column systems facilitates the removal of ammonium nitrogen and heavy metals, stabilizes pH, and enhances the yield of vegetable crops [6–8]. In particular, clinoptilolite has been effectively applied in aquaponics for simultaneous maintenance of water quality and plant growth [9].

ACs and biochar exhibit complementary properties, ensuring efficient adsorption of organic compounds, root exudates, and dissolved organic carbon (Figure 2). Their use helps prevent the accumulation of toxic metabolites, reduce the risk of pathogenic microbial development, and extend the lifespan of nutrient solutions [10,11]. Moreover, the combined use of zeolites and carbon-based materials opens new opportunities for comprehensive solution purification, as demonstrated by studies on integrating such sorbents into vertical hydroponic systems and when using desalinated water [12,13].

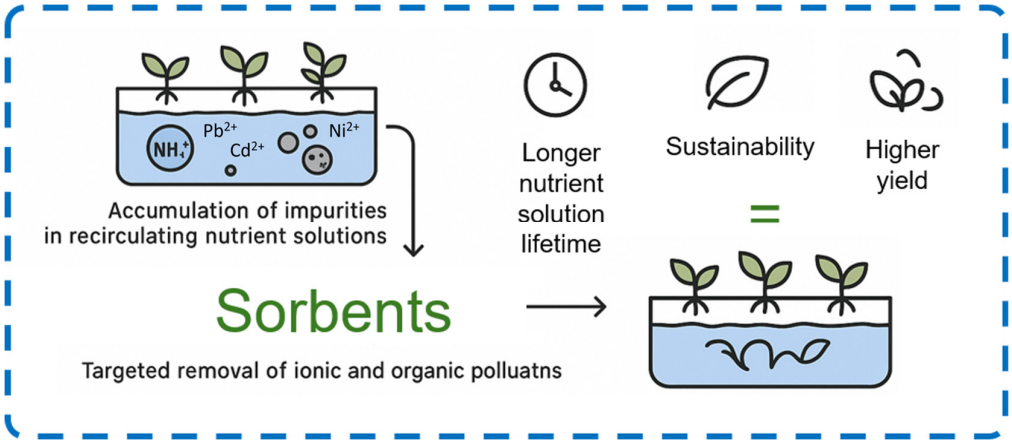


Figure 2. Relevance of Sorbents in Hydroponic Systems.

Thus, the integration of sorbents into hydroponic technologies not only improves the chemical stability of the growing environment but also enhances resource efficiency, ensuring the resilience of production systems to both biotic and abiotic stresses. However, a comprehensive comparative synthesis of zeolites and activated carbons in hydroponic systems, integrating performance, techno-economic, and environmental aspects, remains insufficiently explored.

1.2. Scientific and Practical Challenges in Nutrient Solution Quality Management

Despite the apparent advantages of hydroponics, its large-scale implementation faces several fundamental and practical constraints. The primary challenge is associated with the accumulation of undesirable compounds in the circulating nutrient solution. Excess ammonium nitrogen, produced during the mineralization of organic residues or as a result of fertilizer overuse, can exert phytotoxic effects and reduce crop yields [14]. In parallel, heavy metals (Pb^{2+}, Cd^{2+}, Ni^{2+}) originating from source water or substrates may be present in the solution; their accumulation in plant tissues poses a threat to food safety [15].

Another important limitation is the accumulation of dissolved organic carbon (DOC), which includes root exudates, microbial metabolites, and pesticide residues. These compounds alter the chemical composition of the solution, stimulate the growth of pathogenic microorganisms, and shorten the lifespan of nutrient mixtures. Several studies have shown

that organic metabolites themselves can become the key destabilizing factor and a major cause of secondary infections in hydroponic systems [16,17].

Scientific challenges include the need to study competitive ionic interactions. For instance, zeolites exhibit high selectivity toward NH_4^+; however, they can also sorb K^+ and Ca^{2+} ions, thereby reducing the availability of these essential elements for plants. Carbon-based materials are effective in binding organic compounds, but their sorption capacity is limited by surface saturation and biofouling, which necessitates optimization of operating conditions [18].

Practical challenges are associated with ensuring the long-term performance of sorbents. Key issues include the high cost of production, the need for regeneration, disposal, or replacement of materials after saturation [19]. Moreover, the integration of filtration modules into a closed-loop system requires assessment of hydraulic resistance and its impact on the overall energy efficiency of the system [20]. A particular difficulty lies in developing universal sorbents capable of simultaneously retaining ions, organic compounds, and microbial metabolites, while maintaining structural and chemical stability over prolonged periods of operation [21].

Zeolites have long been recognized as versatile adsorbents, catalysts, and ion exchangers with well-defined structures that enable precise control of molecular partitioning and surface reactivity. Thus, managing the quality of nutrient solutions in hydroponics remains an interdisciplinary challenge, integrating agronomic, chemical, and engineering approaches. Recent reviews have highlighted growing interest in sustainable soilless cultivation technologies and precision control systems [22], as well as the potential role of bioelectrochemical systems in improving nutrient recycling and monitoring [23]. However, these studies have primarily focused on system innovations and automation, with insufficient discussion of sorbent materials, which play a crucial role in nutrient retention and contaminant removal. In contrast, research on adsorption materials has primarily focused on their general properties and application in separation processes [24] or specific experimental applications for nutrient recovery from unconventional sources, such as human urine [25]. However, a comprehensive synthesis linking the physicochemical characteristics of these materials to hydroponic performance and sustainability indicators remains absent.

Activated carbons, on the other hand, are widely used for the adsorption of organic compounds and nutrient recovery in wastewater and agricultural systems. For example [25], demonstrated the use of coconut shell-derived activated carbon for adsorption–desorption processes that convert organic components of human urine into nutrient solutions suitable for hydroponic cultivation. Although such studies reveal the potential of carbon adsorbents for nutrient recycling, a comprehensive analysis comparing their mechanisms of action, performance indicators, and environmental impacts with zeolites is lacking.

Thus, managing the quality of nutrient solutions in hydroponics remains an interdisciplinary challenge that integrates agronomic, chemical, and engineering approaches. Addressing these challenges requires a systematic synthesis of current data on sorbent materials and their interactions in closed hydroponic systems.

The aim of this review is to conduct a comparative analysis of zeolites and ACs used in hydroponic systems, with emphasis on their structural characteristics, mechanisms of ion exchange and adsorption, and roles in the removal of ammonium, heavy metals, and organic contaminants. In addition, this review examines the potential for material modification, including their integration with 2D and 3D structures and transition metal nanoparticles functionalization, which expand their sorption and catalytic properties. Furthermore, the study analyzes the techno-economic and environmental aspects of their application, as well as the prospects for developing combined systems that enhance the sta-

bility and efficiency of hydroponic technologies. Compared with previous reviews [22–25], this work provides a broader synthesis that integrates mechanistic, material, and sustainability perspectives, highlighting opportunities for the development of adaptive and low-waste hydroponic systems).

2. Methods

This review was conducted in accordance with the PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. The protocol for this systematic review was preregistered on the Open Science Framework (OSF), an open-access research registry that serves as an accepted platform for systematic review registration. The registered protocol includes details of the research question, eligibility criteria, search strategy, screening workflow, and planned synthesis procedures. The registration can be accessed through its DOI: [https://doi.org/10.17605/OSF.IO/FE5JZ]. The registration was finalized prior to conducting study selection and data extraction, ensuring transparency and methodological rigor. No amendments were made to the registered protocol, and the review followed the preregistered procedures exactly as planned.

Studies were included if they addressed the use of zeolites, activated carbons, biochar, or similar sorbents in hydroponic systems or comparable aquatic environments, with a focus on adsorption, ion exchange, or techno-economic and environmental assessment. Only peer-reviewed journal articles in English published between 2001 and 2025 were considered.

A literature search was conducted in Scopus, Web of Science, Science Direct, and Google Scholar. The last search was performed on 30 September 2025. Relevant references from key articles were also manually screened to identify additional sources.

Data was extracted manually, and any missing or unclear summary statistics were marked as "not presented". The data were compiled into structured tables and visualized using diagrams to summarize the sorbent's characteristics and applications.

The formal risk of bias assessment was not performed because this study is a descriptive systematic review summarizing experimental and applied studies rather than a quantitative meta-analysis. Sensitivity analyses were not performed, as this review focuses on summarizing trends and key findings rather than statistical effect estimates.

A PRISMA flowchart summarizing the literature search, selection, and inclusion process is provided in the Supplementary Materials.

2.1. Study Selection

The study selection process is presented in Figure 3 PRISMA 2020 flow diagram. A total of 600 records were identified through database searches, and an additional 25 records were found through citation searching. After removing duplicates, the remaining records were screened based on titles and abstracts, followed by a full-text assessment for eligibility.

In total, 102 studies met the inclusion criteria and were incorporated into the final review. Full list of included studies along with their key characteristics is provided in Appendix A Table A1. This supplementary table contains detailed information such as publication year, study design, location, sample size, methods, and main findings, allowing readers to explore the characteristics of each study in depth.

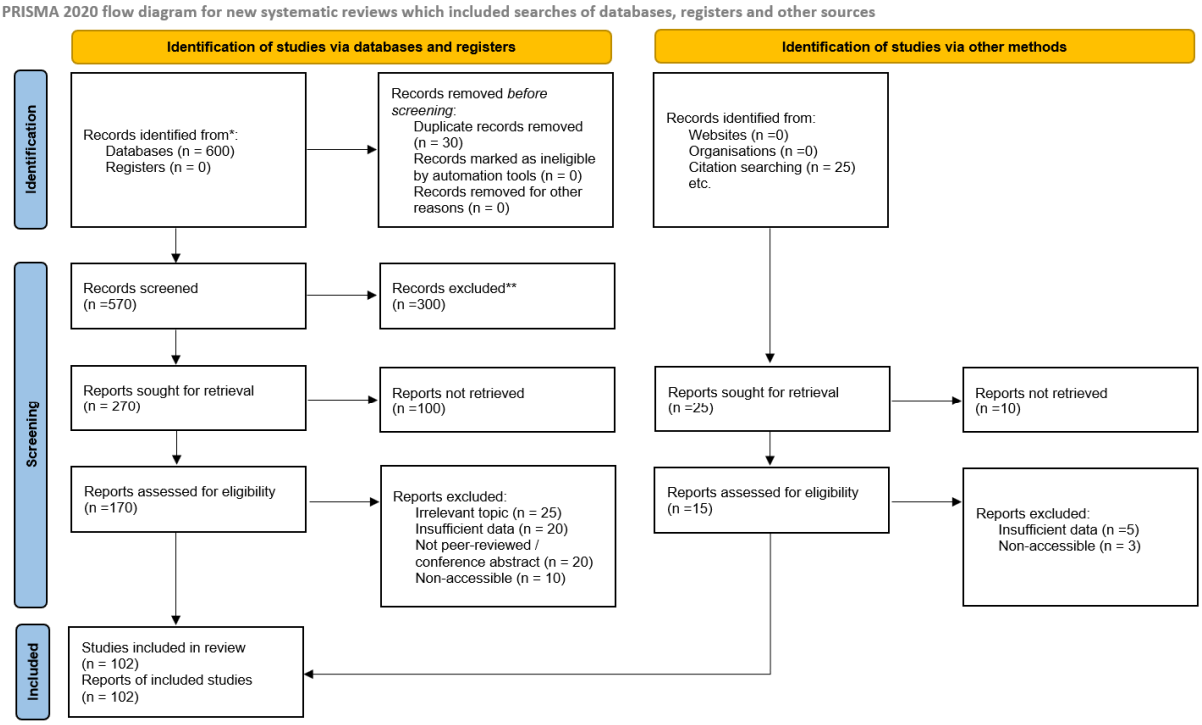


Figure 3. PRISMA 2020 flow diagram illustrating the study selection process [26].

3. Zeolites: Properties and Application in Hydroponics

3.1. Physicochemical Characterization of Zeolite

Natural zeolites are microporous, natural aluminosilicate materials with a specific structure, which is represented by a tetrahedral crystal lattice consisting of SiO^{4-} and AlO^{4-} ions. The SEM image of the natural zeolite (Figure 4a) shows an irregular and heterogeneous surface morphology composed of agglomerated particles of various sizes. The grains exhibit a porous structure with uneven edges, typical of clinoptilolite minerals formed under natural conditions [27].

In the FTIR spectrum of the unmodified natural zeolite (Figure 4c), the stretching vibrations of O–H bonds are not clearly observed around 3436 cm^{-1}. However, a weak absorption band appears near 1632 cm^{-1}, which can be attributed to the bending vibrations of adsorbed water molecules or hydroxyl groups present on the zeolite surface. This indicates that only a small amount of physically adsorbed moisture remains in the structure of the natural clinoptilolite. The degree of resolution of the characteristic absorption bands in the FTIR spectra of mineral forms of zeolites depends on the complexity of their structure. Absorption band in the zeolite spectrum at 1002 cm^{-1}, a silicon–oxygen tetrahedron of Si–O–Si bonds, which is associated with bending vibrations of SiO_4 [27].

The XRD pattern of the zeolite sample confirms that clinoptilolite is the dominant crystalline phase (Figure 4b). Minor diffraction peaks corresponding to albite and mordenite are also detected, indicating their low content in the natural mineral [28].

Table 1 presents the comparative chemical composition of natural zeolites from different deposits. As shown, the SiO_2 and Al_2O_3 contents vary slightly depending on the origin of the samples, with silica generally dominating the composition. The zeolites from Australia and Ukraine exhibit the highest SiO_2 values, indicating a high degree of framework stability typical for clinoptilolite-rich materials (Table 1) [29]. The contents of Fe_2O_3, Na_2O, K_2O, CaO, and MgO differ between deposits, reflecting the influence of local geological

conditions and mineral impurities. The composition of the Kazakhstan sample falls within the general range reported for natural zeolites, confirming its comparable chemical nature.

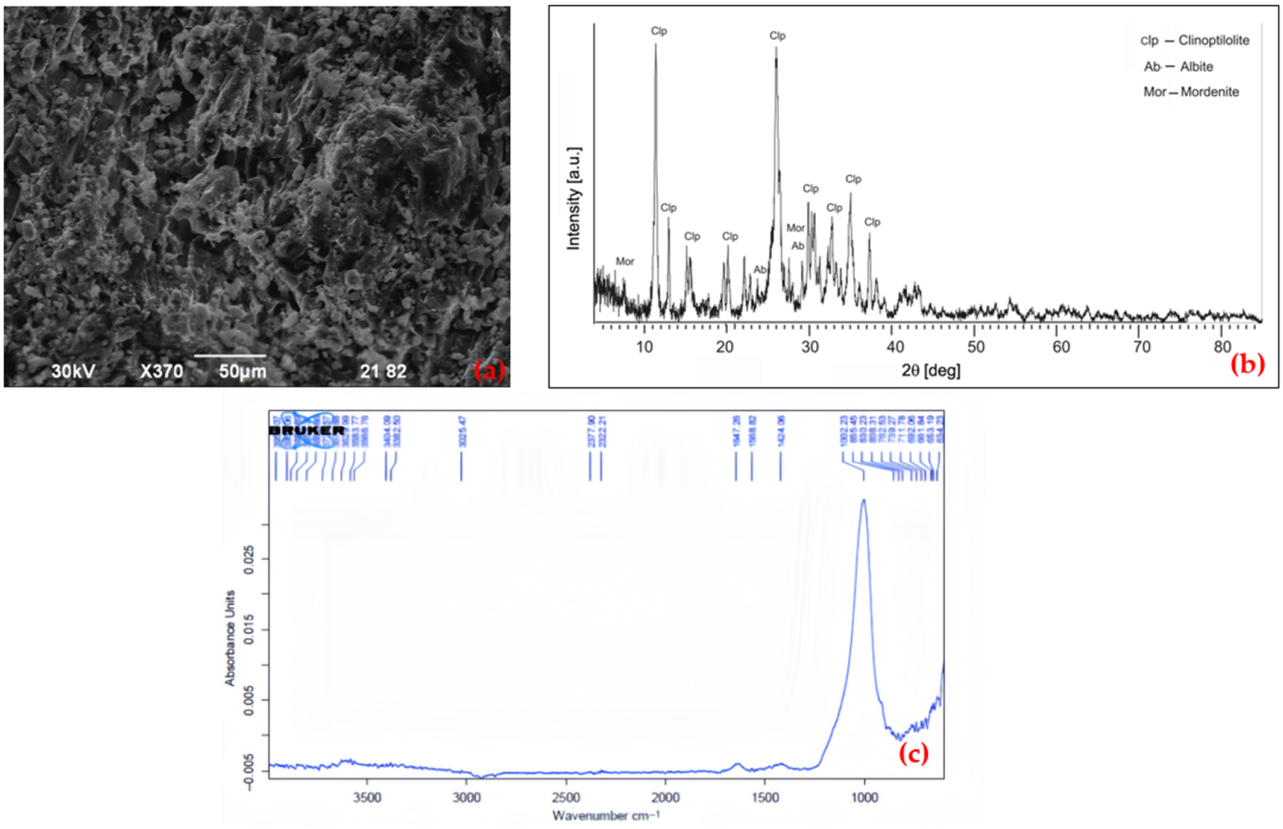


Figure 4. Structural and Physicochemical Properties of Zeolite: (**a**) SEM image of natural zeolite [27], (**b**) XRD pattern of natural zeolite [28], (**c**) FTIR spectrum of natural zeolite [27].

Table 1. Comparative chemical composition of zeolites from different deposits.

Countries	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	Na_2O (%)	K_2O (%)	CaO (%)	MgO (%)
Australia	68.26	12.99	1.37	0.64	4.11	2.09	0.83
China	65.72	13.50	1.30	1.16	3.14	3.10	0.63
Ukraine	68.64	11.50	1.57	0.29	3.12	2.38	0.89
Ecuador	65.80	11.32	3.42	4.10	0.45	1.23	0.96
USA	66.61	12.91	1.70	0.39	2.44	3.18	1.54
Iran [28]	68.17	11.05	0.53	0.64	1.11	3.93	0.62
Kazakhstan [30]	62.2	13.4	5.9	1.6	6.5	5.3	2.2

3.2. Structure, Ion Exchange Mechanisms and Sorption Selectivity

Zeolites are crystalline aluminosilicates with a regular system of micropores formed by SiO_4 and AlO_4 tetrahedra. The substitution of silicon with aluminum in the crystal lattice leads to the formation of negative charges balanced by mobile cations such as Na^+, K^+ and Ca^{2+} [31]. These cations can be exchanged with ions from solution, which determines the high ion exchange capacity and selectivity of zeolites [32].

The selectivity of zeolites with respect to ammonium ion is of particular importance in hydroponic systems. Due to the size of the channels and their high affinity for NH_4^+, clinoptilolite and related minerals effectively remove ammonium from nutrient solutions,

reducing the risk of its toxic accumulation and stabilizing the nitrogen balance [33,34]. In addition, zeolites are able to bind heavy metal cations (Pb^{2+}, Cd^{2+}, Ni^{2+}), which prevents their entry into plants and increases the safety of final products [35].

Ion exchange processes in zeolites are reversible, which makes it possible to regenerate them using saline solutions without destroying the structure. Studies show that even after multiple cycles of use, zeolites retain a significant part of their sorption capacity. This combination of structural stability, high selectivity, and the possibility of reuse makes zeolites promising materials for long-term use in hydroponic systems [36].

Figure 5 shows the mechanism of ion exchange and the factors determining the selectivity of zeolites. Panel (a) shows the crystalline structure of zeolite, in which the negative charge of the frame, resulting from the inclusion of aluminum, determines the ability to bind cations (the conceptual scheme shown in this figure has been adapted and scientifically redesigned by the Avogadro application based on the graphic style and structural principles illustrated in the reference information) [37]; panel (b) shows a SEM snapshot of the morphology of the zeolite particle. Panel (c) illustrates the process of substitution of Na^+ by K^+ and Sr^{2+}: at exchange rates above 80%, the lattice expands, accompanied by a decrease in selectivity. Panel (d) reflects the influence of pH: the competition between H_3O^+ and $Na^+/K^+/Sr^{2+}$ cations lead to the fact that, with increasing pH, hydronium is displaced and the selectivity of zeolite to metals increases. Finally, panel (e) shows the distribution of cations at different crystallographic positions–Site I (D6R ring) and Site II (supercage), which explains the differences in selectivity.

3.3. The Role of Zeolites in the Removal of Ammonium, Cations and Toxic Metals

One of the key functions of zeolites in hydroponic systems is the efficient removal of ammonium ions from nutrient solutions. Excess concentrations of NH_4^+ disrupt the nitrogen balance and can lead to reduced plant productivity, particularly under conditions of high salinity stress. Clinoptilolite, owing to its high selectivity toward ammonium, is considered one of the most promising materials for regulating nitrogen content. Several studies have shown that the addition of zeolites to the substrate or their use in filtration columns results in a significant decrease in NH_4^+ concentration and stabilization of the nitrogen cycle [38].

In addition to ammonium, zeolites demonstrate high efficiency in binding potassium, calcium, and magnesium cations. These processes have a dual effect: on one hand, they prevent the accumulation of excessive concentrations of individual ions, while on the other, they may alter the availability of nutrients for plants. Therefore, the practical value of zeolite application depends on precise control of dosage and operating conditions to avoid deficiencies of essential macronutrients These metals not only exert toxic effects on plants but also pose a threat to human health through the consumption of contaminated produce. The use of zeolites effectively reduces their concentrations, thereby ensuring the safety and environmental sustainability of hydroponic technologies [39].

Figure 6 shows the mechanism and efficiency of ion exchange and heavy metal sorption by zeolite. Zeolites are aluminosilicates with a 3D structure containing exchangeable cations (Na^+, K^+, Ca^{2+}, Mg^{2+}), which can be replaced by heavy metal ions Pb^{2+}, Cd^{2+}, Cu^{2+}, Ni^{2+}, Cr^{3+}, etc. during adsorption (Figure 6a). This selectivity is based on the electrostatic interaction between the charged surfaces of the zeolite and the cations in solution.

As can be seen from the diagram (Figure 6b), the heavy metal removal efficiency using natural zeolite without additives reaches 50–65%, with the highest values recorded for Cu and Cr (64.7% and 56.3%, respectively). The pH dependence graph (Figure 6c) shows that at low pH values (<3), the removal efficiency of all metals is minimal due to competition between H^+ ions for the active sites of the zeolite. With an increase in

pH to 5–6, sorption increases sharply, reaching 90–100%, due to deprotonation of the zeolite surface and increased ion exchange. In a neutral and slightly alkaline environment (pH ≈ 7–8), maximum sorption efficiency is achieved, after which the process stabilizes due to saturation of available exchange sites.

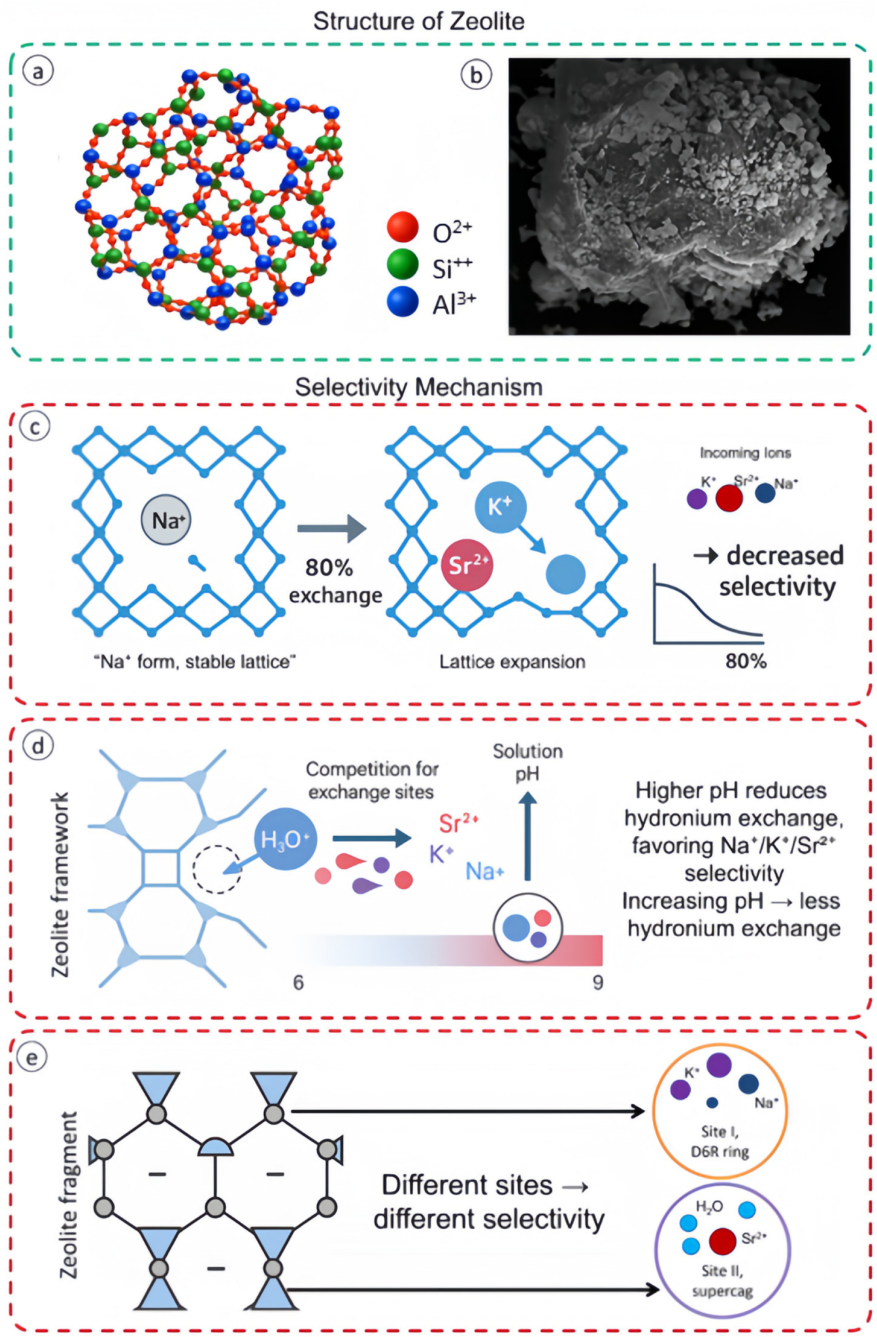


Figure 5. Structure and Ion-Exchange Selectivity of Zeolites materials. (**a**) Crystal structure of zeolite, (**b**) Morphology of zeolite (SEM image), (**c**) Mechanism of selective ion exchange of zeolite, (**d**) Effect of solution pH on ion exchange selectivity of zeolite framework, (**e**) Site-specific cation selectivity in zeolite fragments.

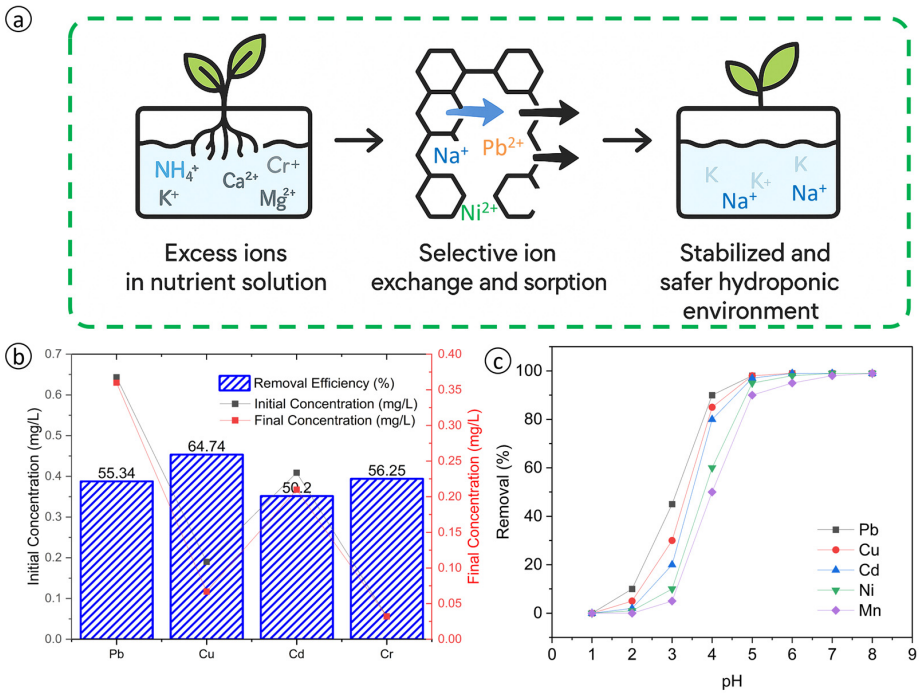


Figure 6. Ion exchange and heavy metal adsorption by zeolite: (**a**) Schematic diagram of the selective ion exchange and nutrient solution stabilization process; (**b**) metal removal efficiency (Pb, Cu, Cd, Cr) using zeolite without additives [40]; (**c**) effect of pH on the removal efficiency of heavy metals (Pb, Cu, Cd, Ni, Mn) [41].

It has been established that zeolites provide selective binding of heavy metal ions under optimal pH conditions of 5–7, simultaneously reducing the concentration of excess cations (NH_4^+, K^+, Ca^{2+}, Mg^{2+}) in hydroponic solutions and stabilizing the chemical composition of the nutrient medium.

3.4. Limitations and Prospects of Zeolite Application

Despite the wide range of favorable properties, the use of zeolites in hydroponic systems is associated with several limitations. One of the key drawbacks is the selectivity of ion exchange, which, under complex solution conditions, may lead to competition for active sites. For example, the high affinity of clinoptilolite for NH_4^+ is accompanied by the sorption of K^+ and Ca^{2+}, which can reduce the availability of macronutrients and cause deficiencies in plants [42].

Another important limitation is the restricted sorption capacity and saturation of the material. Under conditions of intensive operation, the pores of zeolites become rapidly filled, necessitating regular regeneration or replacement. At the same time, conventional methods for restoring sorption capacity–such as washing with saline solutions–are often accompanied by the generation of salt-containing effluents, which impose an additional environmental burden [43].

The physico-mechanical properties of zeolites also impose certain limitations on their use. Their low mechanical strength and tendency to degrade after prolonged contact with water may reduce their effectiveness as an independent substrate. Consequently, zeolites are more commonly used in mixtures with inert materials (such as perlite or vermiculite) or as additives in filtration cartridges [44].

Economic factors likewise play an important role. Although natural zeolites are widely available, their efficiency strongly depends on the deposit characteristics, degree of purification, and post-processing. In some cases, the costs of transportation and modification significantly increase the overall application cost [45].

Future prospects for the use of zeolites in hydroponics are primarily associated with their modification and functionalization. The development of nanostructured zeolites and composites with metal oxides enhances their selectivity and resistance to saturation. A promising direction involves integrating zeolites with 2D and 3D materials such as graphene, g-C_3N_4, and metal–organic frameworks (MOFs), which opens new possibilities for simultaneous sorption and catalytic functions [46].

In addition, the emerging concept of "zeoponics"–the use of zeolites as a long-term substrate for plant cultivation in closed systems, including space programs–has been actively developing. This approach highlights the potential of zeolites as a strategic material for sustainable agriculture under extreme conditions [47].

4. ACs: Properties and Application in Hydroponics

4.1. Morphology, Specific Surface Area and Adsorption Characteristics

ACs are highly porous carbonaceous materials characterized by a developed morphology and a broad pore-size distribution that includes micropores (<2 nm), mesopores (2–50 nm), and macropores (>50 nm). Such a structure provides an exceptionally high specific surface area (often exceeding 1000 m^2/g), which enables the efficient adsorption of a wide range of organic and inorganic compounds [48].

The morphology of ACs directly depends on the raw material (e.g., wood, nutshells, agro-industrial residues) and the activation method used–either physical activation with CO_2 or steam, or chemical activation using phosphates and alkalis. These factors determine both the pore size distribution and the presence of surface functional groups, which in turn influence hydrophilicity, acid–base properties, and electrostatic interactions with ions in solution [49].

A key characteristic of ACs in the context of hydroponics is their high capacity for binding dissolved organic compounds, including root exudates, phenolic metabolites, and pesticide residues. Through a combination of hydrophobic interactions and π–π associations, the carbon matrix effectively retains organic molecules, thereby reducing the risk of pathogenic microbial growth and extending the lifespan of nutrient solutions [50].

Figure 7 illustrates the structural and functional properties of ACs that ensure their high sorption capacity.

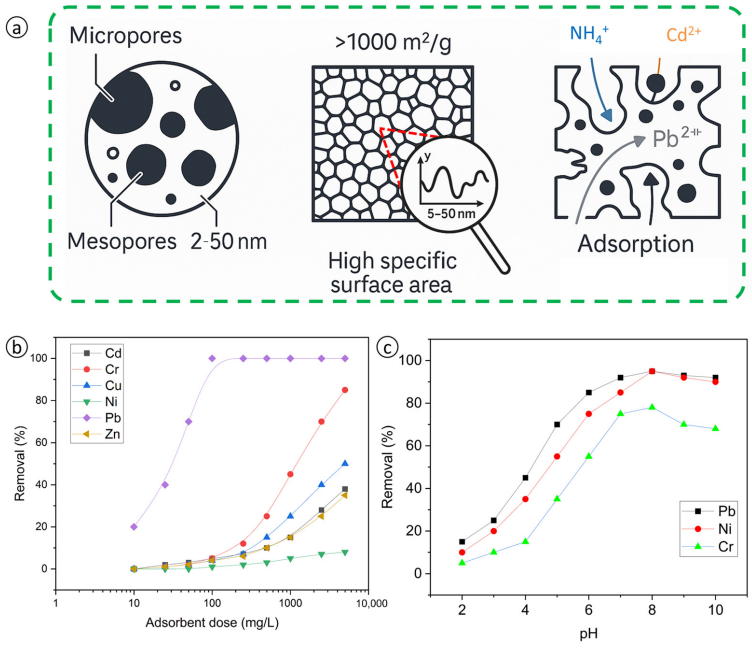


Figure 7. Morphology, specific surface area, and adsorption characteristics of ACs: (**a**) Schematic representation of the pore structure (micro- and mesopores 2–50 nm) and the sorption mechanism of

NH_4^+, Cd^{2+}, and Pb^{2+} ions on a surface with a specific area > 1000 m^2/g; (**b**) Removal efficiency of heavy metals (Cd, Cr, Cu, Ni, Pb, Zn) depending on the adsorbent dose [51]; (**c**) Effect of pH on the degree of metal removal (Pb, Ni, Cr) [52].

In addition, the highly developed surface of ACs facilitates the adsorption of heavy metal cations and ammonium through ion exchange and complexation with oxygen-containing functional groups. Thus, ACs exhibit a high degree of versatility: on one hand, they act as filters for organic contaminants, while on the other, they complement the function of zeolites in stabilizing the inorganic composition of nutrient solutions. The micro- and mesoporous structure creates a large specific surface area (>1000 m^2/g), which facilitates the adsorption of both organic compounds and heavy metal cations. Experimental curves show that with increasing adsorbent dose, the removal efficiency of Pb, Cr, and Cu increases to ~100%, and the optimal pH range (6–8) ensures maximum metal sorption due to reduced competition with H^+ ions and stabilization of complexation on oxygen-containing functional groups on the carbon surface [53].

4.2. The Use of ACs for the Removal of Organic Pollutants and Metabolites

The use of ACs in hydroponic systems is primarily associated with their ability to effectively remove dissolved organic compounds and secondary plant metabolites. Due to the combination of hydrophobic interactions, π–π associations, and hydrogen bonding, AC provides selective binding of a wide range of organic contaminants. This functionality is particularly important in closed-cycle systems, where root exudates and microbial metabolites tend to accumulate and become phytotoxic factors [54].

Compounds that negatively affect plant growth include low-molecular-weight organic acids, phenolic derivatives, and allelochemicals. Their presence in nutrient solutions can inhibit root growth, reduce nutrient uptake, and promote the development of pathogenic microflora. The use of AC helps to lower the concentrations of such substances, thereby stabilizing the biochemical balance of the nutrient medium and extending its service life [55].

The effectiveness of AC is also evident with respect to exogenous organic pollutants such as pesticide residues, pharmaceutical compounds, and endocrine disruptors that may enter the system through water or fertilizers. The removal of these compounds is critical for environmental safety and product quality [56].

In recent years, attention has been focused on modified forms of activated carbon. Surface functionalization with oxygen- or nitrogen-containing groups enhances the hydrophilicity of the material and strengthens its affinity toward polar organic compounds. Nanostructured forms, possessing an increased proportion of meso- and macropores, demonstrate accelerated adsorption kinetics due to reduced diffusion barriers [57].

4.3. Limitations and Prospects of Using ACs

Despite a wide range of positive properties, the use of ACs in hydroponic systems is associated with several limitations. The main issue lies in their low adsorption selectivity: the carbon surface effectively retains a broad spectrum of organic molecules but is not always capable of selectively removing only phytotoxic metabolites. This may lead to competition between target pollutants and essential organomineral components in the solution [58].

Another important factor is the limited durability and the need for regeneration. During prolonged operation, AC becomes saturated with organic matter, undergoes biofouling, and loses its adsorption capacity. Conventional regeneration methods (thermal or chemical) are energy-intensive and may lead to the formation of secondary pollutants. Therefore, under conditions of continuous nutrient solution circulation, the development of low-cost and environmentally friendly regeneration methods is of great importance [59].

The production cost also remains a significant constraint. Although various agro-industrial wastes are widely used as precursors for AC synthesis, the high activation temperatures and the use of chemical agents increase the overall cost compared with zeolites and other mineral sorbents. Furthermore, carbon materials are prone to mechanical degradation and leaching of fine particles, necessitating the development of granulated or composite forms with improved structural stability [60].

Future prospects for AC application in hydroponics are primarily related to surface functionalization and composite design. Modification with oxygen-, nitrogen-, and sulfur-containing groups enhances affinity toward polar organic compounds and ammonium ions. The integration of AC with 2D materials (graphene, g-C_3N_4) and 3D structures (MOFs, COFs) provides not only adsorption but also catalytic degradation of organics, thus expanding material functionality [61].

Special attention is being given to the development of biochar-based composites that combine the low cost and stability of biochar with the high adsorption capacity of AC. Such materials exhibit improved performance in nutrient solution purification and can serve as long-lasting substrates. Another promising direction involves the creation of multifunctional sorption systems combining AC with zeolites or hydrogels, thereby integrating the advantages of different contaminant removal mechanisms [62].

5. Composites of Zeolites and ACs with 2D/3D Materials

5.1. Zeolites and ACs Combined with 2D Materials (Graphene, g-C_3N_4, etc.)

The integration of zeolites and ACs with two-dimensional (2D) materials opens new opportunities for enhancing the efficiency of sorption and catalytic processes in hydroponic systems. Two-dimensional structures such as graphene, graphene oxide (GO), partially reduced graphene (prGO), and graphitic carbon nitride (g-C_3N_4) possess a high specific surface area, rich electronic structure, and tunable surface functionality, providing a synergistic effect when combined with traditional adsorbents [63,64].

Zeolites modified with graphene-based materials exhibit enhanced sorption capacity toward ammonium ions and heavy metals due to the combined effects of ion exchange and π–π interactions. In such composites, graphene layers improve electrical conductivity and create additional diffusion pathways, whereas the microporous framework of zeolites ensures selectivity and structural stability. These hybrids are considered promising materials for managing nutrient balance and removing xenobiotics in recirculating hydroponic solutions [65].

ACs, when modified with GO or g-C_3N_4, acquire enhanced catalytic and photocatalytic properties. The incorporation of g-C_3N_4 into the carbon matrix promotes the photodegradation of organic metabolites and phenolic compounds in hydroponic solutions through the formation of heterojunctions that suppress electron–hole recombination. Graphene layers in AC-based composites increase sorption capacity toward hydrophobic organic molecules while simultaneously improving the mechanical strength and structural stability of granular forms [66].

A promising direction involves the development of multifunctional composites combining zeolites, ACs, and 2D materials. Such hybrid systems integrate ion-exchange, hydrophobic, and π–π interaction mechanisms with photocatalytic degradation of organics, thereby addressing the simultaneous challenges of purification, regeneration, and stabilization of nutrient solutions (Figure 8). Furthermore, the incorporation of 2D structures enhances the electrical conductivity of the composites, paving the way for their application in sensing and intelligent monitoring of hydroponic systems [67].

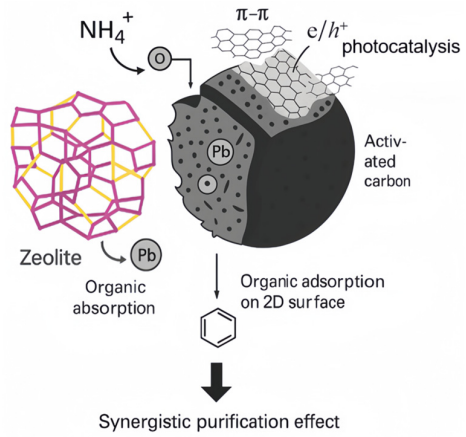


Figure 8. Zeolites and ACs in Combination with 2D Materials (Graphene, g-C_3N_4).

5.2. Composites with 3D Structures (MOF, COF) and Their Functional Features

MOFs and covalent organic frameworks (COFs) are considered promising 3D materials due to their exceptionally high specific surface area, well-defined pore geometry, and tunable functional groups. The integration of zeolites and ACs with these frameworks enables the combination of macro- and microporous carriers with the unique selectivity and adjustable pore architecture of MOF/COF structures [6,68].

Zeolites are characterized by high cation-exchange selectivity and excellent mechanical stability, making them an effective matrix for the growth of MOF structures. Such hybrids exhibit improved performance in removing heavy metals and oxyanions from nutrient solutions, as well as in the controlled release of micronutrients–an especially important feature for closed-loop hydroponic systems. For instance, zeolite–MOF composites have demonstrated higher sorption efficiency for Pb^{2+} and Cd^{2+} compared to their individual components, which is attributed to the synergistic effect between the ion-exchange centers of zeolites and the high surface energy of MOFs [69].

In the case of ACs, integration with MOF and COF is aimed at increasing the adsorption of organic metabolites and resistance to biofouling. Carbon surfaces provide electrochemical conductivity and hydrophobic interactions, while MOF/COF structure the adsorption centers and enhance selectivity. This provides advantages in the removal of phenolic compounds and root exudates, which can negatively affect plant growth [70,71].

COF composites based on zeolites and ACs are characterized by increased chemical stability and the possibility of introducing functional groups (–NH_2, –SO_3H), which enhances their sorption capacity to phosphates and nitrates. In addition, such materials are promising as polishing filters in integrated hydroponic systems, where fine-tuning of the ionic composition of the solution is required [72].

The combination of zeolites and ACs with MOF and COF forms hybrid sorbents of a new generation, which combine the mechanical stability and ion-exchange properties of zeolites, high specific surface area and hydrophobicity of carbon materials, as well as the selectivity and functional variability of 3D frameworks. This opens up opportunities for the creation of intelligent sorption units that adapt to the changing composition of hydroponic solutions [73].

5.3. Comparative Efficiency in Hydroponic Systems

A comparison of zeolites, ACs and their composites with 2D/3D structures under hydroponic conditions shows that the effectiveness of sorbents is determined not only by their internal characteristics, but also by the chemical composition of the nutrient solution. For zeolites, the key factor is the competition of cations: at high concentrations of K^+, characteristic of nutrient media, the exchange capacity for NH_4^+ is noticeably reduced, which accelerates the breakthrough and reduces buffering capacity (Table 2). The use of the Na-form of clinop-

tilolite and the selection of optimal granulometry partially compensate for these limitations, increasing the efficiency of ammonium retention and stabilizing plant nutrition [74–76].

ACs have advantages in removing dissolved organic matter, including phenolic acids and root exudates, which can inhibit growth. Their use in hydroponic systems is associated with improved yields by reducing the toxic load. At the same time, the service life of coal is limited, and after achieving a breakthrough in organic carbon, replacement or regeneration is necessary, which increases operating costs [77].

Integration with 3D structures introduces both new features and limitations. ZIF-8-type frameworks, despite their high specific surface area, are unstable in phosphate solutions and degrade rapidly. In contrast, zirconium MOFs (UiO-66) exhibit stability in water, but their high affinity for phosphates can lead to depletion of macronutrients and plant nutrition disorders. This limits the scope of MOF application in hydroponics to bypass "polishing" modes with strict control of the solution composition [78].

Photocatalytic composites based on g-C_3N_4 and other 2D materials have a pronounced ability to destroy a wide range of organics under visible light, which is promising for the removal of stable metabolites. However, their non-specificity is fraught with the destruction of useful chelates (for example, EDTA–bound iron), which requires careful implementation, mainly in bypass circuits or during episodic sanitation [79–81].

It can be noted that maximum efficiency is achieved with a functional separation of tasks: zeolites are advisable to use for ion balance management (NH_4^+/K^+), while carbon materials and their composites are more effective for controlling organic metabolites. Combined use makes it possible to stabilize the quality of the solution and increases plant productivity in closed hydroponic cycles.

The synergistic effect of zeolite and activated carbon is due to their complementary adsorption mechanisms and surface characteristics. Zeolites with their negatively charged aluminosilicate structure effectively trap cationic compounds such as NH_4^+, heavy metal ions, and other inorganic pollutants. This selective ion exchange process can also reduce biofouling and microbial growth on the surface of activated carbon while maintaining its adsorption capacity for a long time. Meanwhile, activated carbon with its high specific surface area and hydrophobic micro- and mesopores effectively adsorbs organic compounds that might otherwise clog the pores of the zeolite. As a result, the combined use of zeolite and activated carbon increases the overall cleaning efficiency, providing long-term stability and regeneration potential compared to their individual use.

Table 2. Materials and their applicability in hydroponic systems.

The Environment Condition	The Main Risk	The Most Suitable Material	Justification (+Links)
Accumulation of root exudates and organic matter	Growth inhibition, toxicity	Activated carbon (GAC, mesoporous carbon)	Effective reduction in DOC and increase in yield [82]
High concentration of K^+ in the presence of NH_4^+	Competition and reduction in ammonium capacity	Zeolite (Na-form of clinoptilolite)	Higher selectivity for NH_4^+; stabilization of nutrition [83]
Solutions with high phosphate content	Degradation of ZIF-8, depletion of PO_4^{3-} at UiO-66	COF or carbon sorbents; exclude	ZIF-8 ZIF-8 is unstable in PBS; UiO-66 binds PO_4^{3-} [42]
Destruction of stable metabolites is required	Potential degradation of beneficial chelates	Photocatalytic composites (g-C_3N_4) in bypass	High photocatalytic activity, but low selectivity [84]
Long-term operation and low OPEX	Increased operating costs	Zeolite with in situ regeneration with NaCl solutions	Multiple cycles without loss of mechanics [85]
Maintaining the NH_4^+/K^+ balance and reducing DOC	Deficiency/toxicity risks	Combination of zeolite and activated carbon	Separation of functions stabilizes the system and improves productivity [86]

Table 3 synthesizes the key performance characteristics of zeolites, activated carbons, and composite sorbents, highlighting differences in adsorption mechanisms and suitability for various contaminants.

Table 3. Comparative Evaluation of Zeolites, Activated Carbons, and Their Composites Across Key Performance Metrics.

Indicator	Zeolites	Activated Carbon	Zeolite-Carbon Composites
primary mechanism	ion exchange; molecular sieve	physical adsorption; π–π interactions	ion exchange + adsorption; catalytic effects
key target pollutants	NH_4^+, K^+, heavy metals	DOC, pesticides, organic compounds	NH4+, heavy metals, organic matter
advantages	high selectivity; structural stability; low cost	large surface area (~1000 m^2/g); high organic capacity	synergy, increased capacity, sustainability
disadvantages/limitations	ion competition; weak adsorption of organic substances	surface contamination; possible high cost	complexity of synthesis; variability of properties
regeneration potential	light (chemical regeneration)	complex (thermal regeneration degrades properties)	average; depends on the composition

6. Sorbents as Carriers for Transition Metal Nanoparticles

6.1. Zeolites Modified with Transition Metals: Catalytic Functions

Zeolites are among the most extensively studied carriers for ions and nanoparticles of transition metals due to their high cation-exchange capacity, well-defined porous structure, and stability under aggressive conditions. The incorporation of cations such as Cu^{2+}, Fe^{3+}, Mn^{2+}, Co^{2+}, or Ni^{2+} into the channels and cavities of zeolites imparts pronounced catalytic properties, enabling these materials to function not only as sorbents but also as active centers for redox reactions [87].

According to literature data, Cu- and Fe-containing zeolites exhibit high activity in the catalytic oxidation of ammonium and organic contaminants in aqueous media. These materials operate via the generation of hydroxyl radicals (OH), promoting deep oxidation to harmless end products (N_2, CO_2, H_2O) [88]. In hydroponic systems, this opens up prospects for the use of metal-modified zeolites in controlling ammonium nitrogen and organic metabolites that are poorly removed by purely sorptive methods.

Particular attention has been given to Mn-modified zeolites, which exhibit catalytic activity due to various forms of MnOx embedded in the structure or in contact with the surface. The various oxidation states of manganese ensure efficient oxidation of organic compounds, and the combination of Mn with zeolites improves adsorption and catalytic purification of solutions, reducing the load on carbon sorbents and increasing the stability of hydroponic systems [89].

Figure 9 presents a schematic overview of possible mechanisms in transition-metal-modified zeolites. The incorporation of Fe^{3+}, Cu^{2+}, and Mn^{2+} ions via ion exchange introduces redox-active sites that may enhance adsorption, ion exchange, and limited oxidation reactions under mild conditions. Although complete catalytic oxidation of ammonium and organic molecules requires higher temperatures, these modified zeolites can still promote redox buffering, nutrient stabilization, and suppression of harmful compound accumulation in hydroponic nutrient solutions.

An additional advantage lies in the ability of zeolites to stabilize metal nanoparticles within their micropores, preventing aggregation and leaching of active centers. For example, the incorporation of Pd nanoparticles into zeolite-alumina systems have been shown to

improve catalytic performance in hydrogenation and oxidation reactions of organic compounds. These approaches can be adapted to aqueous environments, including hydroponic systems, where selective degradation of organic toxicants is required [90].

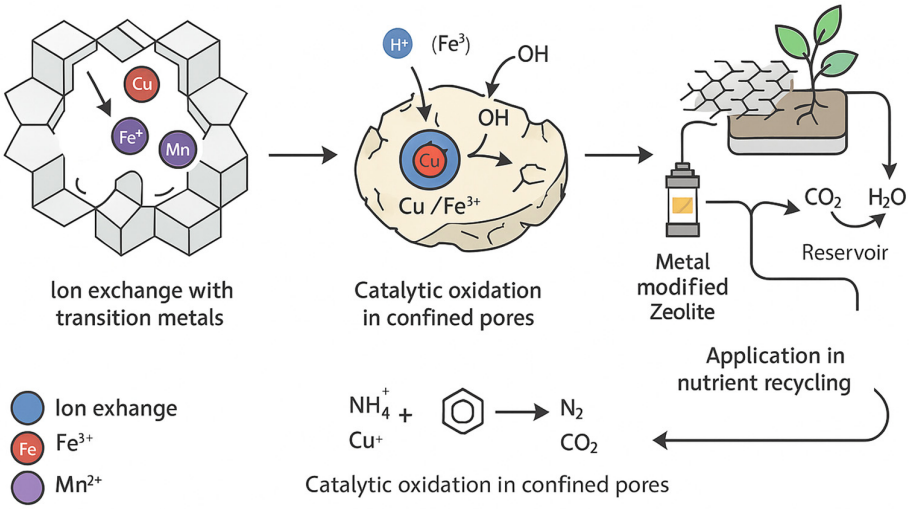


Figure 9. Transition-Metal-Modified Zeolites: Sorption and Catalytic Functions in Hydroponic Systems.

The modification of zeolites with transition metals leads to the development of multifunctional materials that combine sorptive, ion-exchange, and catalytic properties. Their integration into hydroponic systems can significantly expand the functionality of filtration units-from simple ion composition correction to active management of organic and nitrogen-containing contaminants.

6.2. Transition-Metal-Modified ACs for Environmental and Hydroponic Applications

ACs functionalized with transition metals represent a promising class of hybrid materials that combine adsorption, ion exchange, and redox catalytic properties. The integration of metal species such as Fe, Mn, Ni, Cu, and Co into the porous carbon matrix creates redox-active sites capable of simultaneously binding, transforming, and stabilizing inorganic and organic species in aqueous systems [91]. Metal incorporation is typically achieved by impregnation or co-precipitation, followed by thermal activation, resulting in uniformly distributed nanoparticles or ionic clusters anchored to oxygen-containing surface groups (–OH, –COOH, –C=O) [92].

Among these composites, Fe-modified ACs (Fe–ACs) have received particular attention due to their multifunctionality. The presence of Fe^{2+}/Fe^{3+} redox pairs enhances the material's capacity to remove oxyanions such as PO_4^{3-} and AsO_4^{3-} through complexation and surface precipitation, while also promoting oxidation-reduction reactions that stabilize nutrient composition in hydroponic media. Studies have shown that Fe_3O_4-coated ACs exhibit strong affinity toward phosphate and ammonium ions, preventing their excessive accumulation and thus mitigating nutrient imbalance and microbial overgrowth in closed hydroponic systems. Furthermore, the magnetic nature of Fe_3O_4 facilitates rapid separation and reusability of the composite, improving operational safety and sustainability [93].

Other transition metals impart complementary functions. Mn- and Cu-modified carbons catalyze Fenton-like reactions and enhance the degradation of organic metabolites and pesticide residues, which commonly accumulate in nutrient solutions during plant growth. Ni- and Co-doped carbons, while primarily studied for electrochemical applications, also demonstrate redox behavior that may contribute to the regulation of reactive oxygen species and ionic balance in hydroponic environments [94].

The transition-metal-modified ACs function as multifunctional materials, integrating adsorption, catalysis, and magnetic recovery. Their implementation in hydroponic systems offers an effective means of maintaining nutrient stability, minimizing toxic ion accumulation, and enabling the controlled removal of organic and inorganic contaminants, thereby supporting sustainable and high-yield plant production [95].

The results illustrated in Figure 10 demonstrate the multifunctional performance of Fe-modified AC (Fe–AC) as both an adsorbent and a reactive barrier for phosphate control in aqueous and soil systems. In Figure 10a, the adsorption isotherms reveal that Fe incorporation significantly increases the phosphate affinity compared to pristine activated carbon, confirming the formation of Fe^{2+}/Fe^{3+} redox sites that enhance surface complexation and electrostatic binding with PO_4^{3-} species. This mechanism aligns with the dual adsorption–redox functionality described earlier, where transition-metal centers stabilize anionic nutrients through coordination and partial redox conversion.

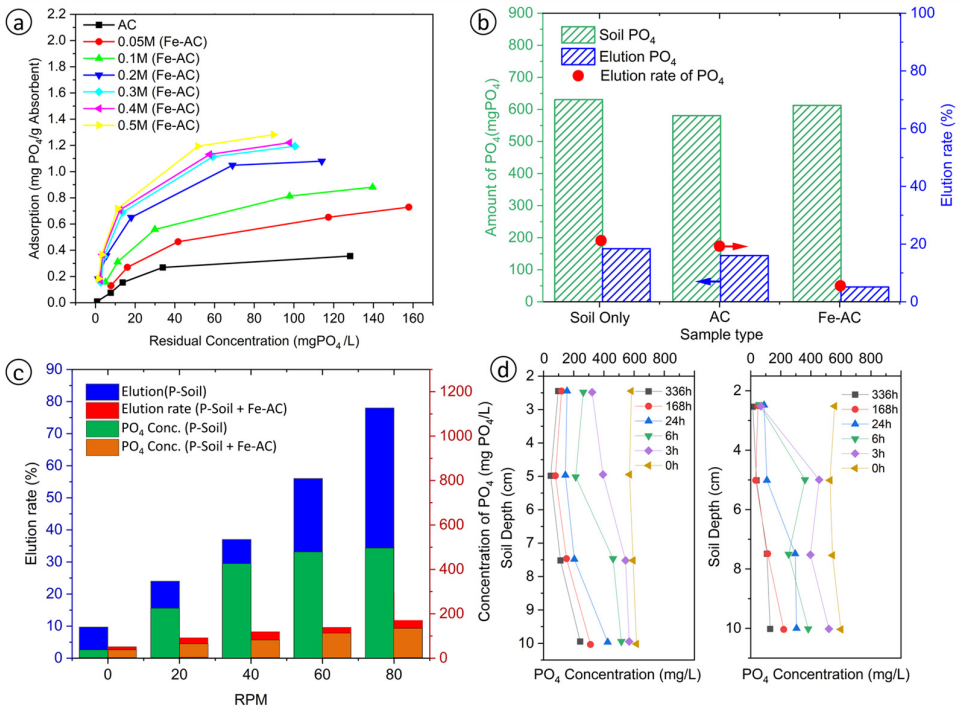


Figure 10. Phosphate adsorption and release characteristics of Fe-modified activated carbon [96]: (**a**) adsorption isotherms; (**b**) static soil system; (**c**) hydraulic flow conditions; (**d**) phosphate profile with soil depth.

Under static soil conditions (Figure 10b), the Fe–AC layer drastically suppressed phosphate leaching relative to unmodified soil or bare activated carbon, indicating its capacity to immobilize soluble phosphorus and prevent eutrophication. When hydraulic flow was introduced (Figure 10c), the Fe–AC maintained low elution rates (<10%) even at high turbulence, highlighting its structural stability and persistent adsorption efficiency under dynamic water movement–conditions typical for hydroponic circulation or irrigation systems. The vertical concentration profiles in Figure 10d further confirm that Fe–AC effectively restricted phosphate migration through the sediment column, maintaining a steep concentration gradient and minimizing nutrient release to the overlying water.

Collectively, these results emphasize that Fe-modified carbons function not only as high-capacity phosphate sorbents but also as reactive capping and stabilization agents, combining adsorption, ion exchange, and Fe-centered redox processes. In hydroponic applications, such properties can mitigate nutrient losses, suppress microbial overgrowth by controlling phosphate bioavailability, and sustain ionic equilibrium in recirculating

nutrient solutions—illustrating the broader potential of transition-metal-modified ACs as multifunctional materials for water purification and sustainable plant cultivation.

7. Techno-Economic Analysis and Life-Cycle Assessment

7.1. Techno-Economic Considerations

Natural zeolite is widely regarded as a low-cost, readily available adsorbent due to abundant mineral deposits and minimal processing (Table 4) [95]. By contrast, chemically modified zeolites (acid-treated, ion-exchanged or metal-impregnated) incur higher capital cost because of extra reagents and thermal energy in their manufacture [97]. AC production is energy-intensive, so high-grade carbons tend to have moderate-to-high costs. In practice AC from waste biomass can be relatively inexpensive per kg, but its true cost should account for higher adsorption capacity of engineered carbons [98].

Table 4. Economic and environmental trade-offs of zeolites and activated carbon in hydroponics.

Feature	Natural Zeolite	Modified Zeolite	Activated Carbon (AC)
Cost	Low: abundant clinoptilolite is inexpensive [99]	Higher: chemical or thermal treatment raises cost [97]	Moderate–High: carbonization and activation energy cost [100]
Production footprint	Lower: mainly mining and milling	Moderate: plus reagents/heat for modification	Highest: high-temp pyrolysis and chemical activation [101]
Adsorption (nutrients)	Selectively exchanges cations (NH_4^+, K^+, etc.), retaining nutrients [100]	Enhanced capacity/selectivity (e.g., metal-loaded for P removal) [99]	Non-selective: strong organics removal, but also binds NO_3^-/PO_4^{3-} [23]
Regeneration	Easy: salt or base wash, low-energy; structure stable [99]	Similar approach; may need stronger reagents for heavy modifications	Difficult: thermal (>600 °C) or chemicals (high energy/cost) [101]
Operational benefits	Extends solution life (slow-release of nutrients); reduces fertilizer needs [100]	As natural, often higher removal rates; tailored pollutant uptake	Extends reuse by removing organics; but depletes nutrients [23]
End-of-life	Non-hazardous; can be used as nutrient-rich soil amendment [100]	Similar reuse as soil amendment; caution if loaded with added metals	Spent AC (if organics only) can be reactivated; otherwise disposed (generally inert if no toxic load)

From a techno-economic perspective, a critical consideration lies in evaluating the relative feasibility and cost-effectiveness of sorbent regeneration as opposed to complete material replacement. Regeneration (e.g., saline or basic wash for zeolites, thermal or chemical treatment for AC) avoids frequent purchase of fresh media but demands energy and labor. In full-scale water treatment, regenerated GAC typically retains 60–80% of virgin capacity after one cycle, and its cost can be roughly half that of new carbon [102]. Zeolites are often regenerated with NaCl or NaOH brines, which is relatively low-cost and can recycle the media many times [97]. However, each regeneration cycle degrades performance modestly, and eventual replacement is needed.

7.2. Agricultural and Water-Saving Benefits

Natural zeolites have high cation-exchange capacities for NH_4^+, K^+, etc., acting as slow-release reservoirs in solution. In practice this means nutrient solutions can be recycled

longer before major fertilizer top-ups. For example, studies in soil/soilless culture show zeolites reduce nutrient leaching and volatilization, and gradually release adsorbed N or P back to plants [100]. By contrast, AC is non-selective: it effectively removes phytotoxic organics, but it can also adsorb significant amounts of nitrate and phosphate [23]. Thus, AC polishing can improve hydroponic solution quality, but often at the cost of depleting nutrients (necessitating more fertilizer). Overall, system models suggest that even modest extension of solution life due to sorbent use can yield substantial fertilizer cost savings, since hydroponic fertigation can represent a large part of operating expenses.

7.3. Environmental Footprint and Life-Cycle Assessment

Activated carbon manufacture (especially with KOH or steam) is energy- and emission-intensive: recent LCA data report ~27–28 MJ and ~1.2 kg CO_2 equivalent per kg of AC produced [101]. High-temperature pyrolysis is the main contributor to energy use and emissions. Zeolite production varies: simply mining and crushing clinoptilolite has a modest footprint, but synthesizing zeolites from chemical precursors is more impactful. Indeed, LCA studies show natural-mineral derived zeolites have substantially lower impacts across categories than purely synthetic routes [102]. Any chemical modification adds upstream footprint from reagents and processing. On balance, natural zeolite media tend to have a lower cradle-to-gate environmental cost than activated carbon.

In use, both sorbents deliver environmental benefits: by recycling nutrient solution, they avoid manufacturing and transporting extra fertilizer and reduce nutrient runoff. For instance, zeolites can adsorb tens of mg N/kg (even >30 mg/g NH_4^+ [97]) and similar P levels, preventing their release. The water savings in closed hydroponics can be further improved by sorbent-based solution recirculation. Studies also note that sorbent-aided systems emit less N_2O and NO_x and leach less nitrate to the environment [100].

At end-of-life, spent sorbents have distinct fates. Loaded zeolite containing plant nutrients is generally non-hazardous and can be recycled as a slow-release soil amendment or incorporated into fertilizer blends [100]. For example, nutrient-charged clinoptilolite has been used as a soil conditioner to release NH_4^+ and K^+ over time. In contrast, spent AC) can often be thermally reactivated for one or two more cycles or, if contamination (e.g., phenolics) is low, simply discarded without special hazard. If AC has sequestered heavy metals or organic toxins, disposal must follow regulations (often incineration or landfilling). Importantly, studies highlight that zeolite media can be regenerated and reused multiple times [97], while AC's regeneration efficiency falls after several cycles. Ultimately, nutrient-saturated zeolite tends to be beneficially reused, whereas exhausted AC is usually recycled (reactivated) or safely disposed.

8. Conclusions

A comparative analysis of zeolites, activated carbons, and their modified transition metals and composite derivatives shows their important role in maintaining the chemical stability and environmental safety of hydroponic systems. Natural zeolites, with their crystalline structure and high ion exchange capacity, demonstrate excellent efficiency in regulating the content of ammonium and cations, as well as in removing heavy metals. On the contrary, activated carbon has greater efficiency in the adsorption of organic compounds, root secretions, and secondary metabolites due to its large surface area and regulated pore structure. Thus, while zeolites dominate in the fight against inorganic ions, activated carbons outperform them in the fight against organic pollutants, which makes their combined use particularly effective.

The integration of zeolites and ACs with 2D (graphene, g-C_3N_4) and 3D (MOF, COF) frameworks leads to the creation of multifunctional sorbents that combine adsorption, ion exchange, photocatalysis, and nutrient regulation. Materials modified with transition

metals (Fe-, Mn-, Cu-, Ni-, and cofunctionalized carbons and zeolites) additionally increase productivity by introducing redox centers that stabilize nutrients, inhibit phosphate leaching, and prevent eutrophication. These hybrid systems represent a new generation of adaptive "intelligent" materials capable of responding to dynamic hydroponic conditions.

From a technical and economic point of view, zeolite and carbon-based composites contribute to the introduction of cyclic and sustainable hydroponics methods, reducing fertilizer and water consumption, extending the service life of nutrient solutions, and minimizing waste emissions. However, existing studies still lack consistent long-term data on field productivity, regeneration efficiency, and environmental impacts. Therefore, future research should focus on in situ regeneration mechanisms, long-term nutrient stability, and life cycle assessment of these multifunctional sorbents. Overall, this review shows that a reasonable combination of zeolites and activated carbons, especially when combined with 2D/3D frameworks, provides a synergistic effect to create more sustainable, efficient, and circular hydroponic systems. Further development of adaptive, self-healing sorbents will not only increase agricultural productivity but also reduce the negative impact on the environment, paving the way for sustainable food production in conditions of limited resources.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/su172410977/s1. PRISMA 2020 Checklist [26].

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Abbreviations

The following abbreviations are used in this manuscript:

ACs	Activated carbons
GO	Graphene oxide
prGO	Partially reduced graphene
MOFs	Metal–organic frameworks
COFs	Covalent organic frameworks

Appendix A

Following the rigorous study selection process detailed in Section 2.1, a total of 102 individual studies met all inclusion criteria and form the basis of this review. Full characteristics of each included study are provided in detail below in Appendix A Table A1. This comprehensive table serves as a supplementary resource, detailing the citation, study type/design, system/model used, intervention/exposure, key outcomes measured, and a summary of the relevant findings for every source.

Table A1. Study characteristics.

Ref. No	Study ID (Citation, Year)	Study Type/Design	System/Plant Model	Intervention/Exposure Details	Key Outcomes Measured	Relevant Findings (Summary)
[1]	Chatzigeorgiou et al., 2022	Experimental Study	Vine leaves in a Mediterranean greenhouse (Hydroponic NFT/Perlite)	Comparison of substrates (Perlite, Perlite-Attapulgite, Perlite-Zeolite)	Yield, Carbon Footprint (CFP), Phenols, Nutrients	Perlite treatment yielded highest leaf number and lowest CFP.
[2]	Li et al., 2022	Experimental Study	Hydroponic Vertical Greening System (VGS)	Optimization of operating conditions for blackwater treatment	Removal efficiencies for C, N, P; plant growth	System effectively treated blackwater; removal rates optimized at specific conditions.
[3]	Awad et al., 2021	Experimental Study	Cabbage, dill, red lettuce (NFT Hydroponics)	Substrate comparison: Perlite (PL) vs. Rice Husk Biochar (RB) vs. PL+RB mix	Shoot length, fresh/dry mass, leaf nutrient content	PL+RB mixture doubled the yield and enhanced micronutrient content compared to PL alone.
[4]	Dyer, 2001	Book Chapter/Technical Note	N/A (Theoretical/Lab context)	N/A	Definition of Ion Exchange Capacity (IEC)	Explains the fundamental concept and how to estimate IEC in zeolites.
[5]	Sambo et al., 2019	Review Article	N/A (Conceptual/Review)	Review of hydroponic solutions and smart agriculture tech	Opportunities and limitations of soilless systems	Highlights issues and opportunities in nutrient management for soilless production.
[6]	Bindra et al., 2023	Experimental Study (Lab/Pot)	Tomato plant	MOF/Zeolite composite for targeted nutrient release	Nutrient release profile, plant uptake	Developed a smart fertilizer mechanism using zeolite composites.
[7]	Mussina et al., 2025	Experimental Study (Soil)	*Aesculus hippocastanum* (Horse chestnut)	Evaluation in artificial *soil* contamination	Phytoremediation potential	Study focused on soil remediation, not directly hydroponics.
[8]	Mosa et al., 2019	Experimental Study	Tomato (*Lycopersicon esculentum* L.) in NFT	Biochar filters added to nutrient solution with Nickel (Ni) contamination	Ni toxicity reduction, plant growth	Biochar filters significantly reduced toxic effects of Ni on tomato plants.
[9]	Olasehinde, 2025	Review/Perspective Article	N/A	Review of biodegradable growth media	Suitability of alternatives (e.g., coconut coir, peat, biochar)	Discusses sustainable alternatives to traditional substrates.

Table A1. *Cont.*

Ref. No	Study ID (Citation, Year)	Study Type/Design	System/Plant Model	Intervention/Exposure Details	Key Outcomes Measured	Relevant Findings (Summary)
[10]	Calabria et al., 2019	Experimental Study/Pilot	Lettuce (*Lactuca sativa*) in vertical hydroponics	Zeolite ion exchange column for treating anaerobic wastewater	N recovery efficiency, lettuce fertigation success	Demonstrated successful recovery of N and subsequent safe reuse for plant growth.
[11]	El-Shal. et al., 2022	Experimental Study	Alfalfa plants (hydroponics)	Application of NPK nano-fertilizers under different water qualities	Plant growth metrics, nutrient uptake	Nano-fertilizers improved plant performance and nutrient utilization.
[12]	Pan et al., 2016	Experimental Study	Rice and Wheat seedlings (Hydroponic)	Varying ammonia/ammonium concentrations	Root morphology changes, N concentration in leaves/roots	Established threshold levels for toxicity symptoms induced by high ammonium concentration.
[13]	Nurbaity et al., 2019	Conference Paper/Study	N/A (Methodology focus)	Optimization of hydroponic technology	Production yield of mycorrhiza biofertilizer	Study focused on the production of biofertilizer using hydroponics methodology.
[14]	Vehar et al., 2025	Experimental Study	Tomatoes (hydroponic)	Exposure to contaminants of emerging concern (CECs)	Primary and secondary metabolites in fruit	Assessed the uptake and influence of pharmaceuticals/pollutants on crop safety/quality.
[15]	Li et al., 2020	Experimental Study	N/A (Zeolite material study)	Ammonium-modified clinoptilolite ion exchange experiments	Cation exchange capacity (CEC), selectivity for methane/nitrogen	Lab study characterizing zeolite material properties for gas/liquid separation.
[16]	Korotta-Gamage, S.M., Sathasivan, A., 2017	Experimental Study	N/A (Water treatment study)	Biologically activated carbon (BAC) treatment of surface water	Organic carbon removal efficiency (DOC, UV-254)	BAC effectively removed organic carbon; process optimization was studied.
[17]	Yang et al., 2022	Experimental Study	Hydroponic Rice and Wheat seedlings	Irrigation with “activated water” (magnetic treatment)	Root morphology metrics (length, volume, surface area)	Activated water significantly improved root development in both crops.
[18]	Suryaningtyas et al., 2023	Conference Paper/Review	N/A (Medium development)	Zeoponic media review (Zeolite/compost mix)	Material characteristics, application potential	Discusses potential of zeoponics as a sustainable growing medium.

Table A1. *Cont.*

Ref. No	Study ID (Citation, Year)	Study Type/Design	System/Plant Model	Intervention/Exposure Details	Key Outcomes Measured	Relevant Findings (Summary)
[19]	Zahid et al., 2021	Experimental Study	N/A (Water purification study)	Modification of natural clinoptilolite and mordenite	Heavy metal removal efficiency	Demonstrated effective application of local Kazakhstan zeolites for water treatment.
[20]	Rashed & Pal.anisamy, 2018	Book Chapter/Review	N/A (Review of Zeolites)	Review of adsorption/ion exchange properties of zeolites	General properties and application overview	Provides foundational information on zeolite use in water treatment.
[21]	Adam et al., 2025	Conference Paper/Study	N/A (Wastewater treatment focus)	Application of natural zeolite clinoptilolite for ammonia removal	Ammonia removal efficiency	Zeolite was effective for ammonia removal in lab-scale wastewater treatment.
[22]	Fuentes-Peñailillo et al., 2024	Review Article	N/A (Review of tech)	Review of sustainable technologies for soilless production	Technology assessment	Discusses new tech including potential of substrates and nutrient solutions.
[23]	Wang et al., 2024	Review Article	N/A (Review of systems)	Review of current hydroponic practices and bioelectrochemical systems	System assessment and future roles	Evaluates current systems and innovative solutions for sustainable production.
[24]	Pérez-Botella et al., 2022	Review Article	N/A (Review of Zeolites)	Review of zeolites in adsorption processes	Adsorption mechanisms	Comprehensive review of zeolite use in various adsorption applications.
[25]	Van et al., 2021	Experimental Study/Pilot	Lettuce	Production of hydroponic solution from human urine with activated carbon	N, P, K recovery efficiency; plant growth	Developed a viable method to recycle nutrients from urine for fertigation.
[27]	Seitzhanova et al., 2023	Experimental Study	N/A (Material science)	Influence of heat treatment on zeolite sorption characteristics	Sorption capacity, physical properties	Focused on how heat treatment affects zeolite properties for water purification.
[28]	Mansouri et al., 2013	Experimental Study	N/A (Material characterization)	Characterization of natural zeolite-clinoptilolite	Porosity, structural properties	Studied the fundamental properties of a specific zeolite material.

Table A1. *Cont.*

Ref. No	Study ID (Citation, Year)	Study Type/Design	System/Plant Model	Intervention/Exposure Details	Key Outcomes Measured	Relevant Findings (Summary)
[29]	Elshorbagy & Chowdhury, 2013	Book	N/A (General topic)	N/A	N/A	An edited book providing a general overview of water treatment.
[30]	Kenzhal.iyev et al., 2020	Experimental Study	N/A (Material modification)	Modification of natural Kazakhstan sorbents	Material characteristics, sorption properties	Focused on improving the properties of local sorbent materials.
[31]	Wasielewski et al., 2020	Experimental Study	N/A (Wastewater sludge)	Application of natural clinoptilolite for ammonium removal	Ammonium removal from sludge water	Zeolite proved effective in lab-scale ammonium removal from specific wastewater.
[32]	Cheng & Ding, 2015	Experimental Study	N/A (Water treatment study)	Natural and modified zeolite for ammonium removal	Kinetic, equilibrium, thermodynamic parameters	Characterized the mechanisms and efficiency of ammonium removal by zeolite.
[33]	Nogueira et al., 2025	Experimental Study	N/A (Wastewater treatment study)	Zeolite-SPION nanocomposite use	Ammonium and heavy metal removal efficiency	Developed a novel composite material effective at removing multiple pollutants.
[34]	Rahmani et al., 2009	Experimental Study	N/A (Water treatment study)	Clinoptilolite regeneration by air stripping	Regeneration efficiency	Focused on the practical aspect of reusing zeolite material after saturation.
[35]	Ofiera & Kazner, 2025	Experimental Study	N/A (Water treatment study)	Influence of ammonium on heavy metal adsorption	Heavy metal removal efficiency	Investigated competitive adsorption dynamics between ammonium and heavy metals on zeolites.
[36]	Murkani et al., 2015	Experimental Study	N/A (Water treatment study)	Natural clinoptilolite for removal of ammonium and nitrate	Removal efficiency (%)	Zeolite was highly effective for ammonium removal, but not nitrate removal.
[37]	Nakano et al., 2013	Experimental Study	N/A (Material science)	Potassium metals loaded into zeolite LSX cages	Magnetic and electronic properties	Study focused purely on material physics and magnetism.
[38]	Velarde et al., 2023	Review Article	N/A (Review of zeolites)	Adsorption of heavy metals on natural zeolites	Review of mechanisms and applications	Comprehensive review of using zeolites for heavy metal remediation.

Table A1. *Cont.*

Ref. No	Study ID (Citation, Year)	Study Type/Design	System/Plant Model	Intervention/Exposure Details	Key Outcomes Measured	Relevant Findings (Summary)
[39]	Montégut et al., 2016	Experimental Study	N/A (Wastewater study)	Use of clinoptilolite, chabazite, and faujasite zeolites	Ammonium and Potassium removal efficiency	Compared different zeolite types for nutrient recovery from swine manure.
[40]	Hal.imoon & Yin, 2010	Experimental Study	N/A (Wastewater study)	Zeolite use for heavy metal removal from textile wastewater	Metal removal efficiency	Demonstrated effectiveness in specific industrial wastewater context.
[41]	He et al., 2016	Experimental Study	N/A (Material synthesis)	Zeolite synthesized from fly ash for heavy metal removal	Synthesis process, metal removal efficiency	Created effective zeolite material from waste products.
[42]	Castro et al., 2021	Experimental Study (Field Scale)	Non-sewered sanitation system	Zeolite application and regeneration in a field unit	Ammonium removal from real-world wastewater	Field study showing practicality and regeneration methods for large-scale use.
[43]	Guida et al., 2020	Experimental Study (Lab/Pilot)	N/A (Wastewater treatment study)	Evaluation of different zeolites for ammonium removal	Ammonium removal capacity (mg/g)	Compared several commercial zeolites for efficiency in municipal wastewater treatment.
[44]	Subramanian et al., 2023	Review Article	N/A (Material synthesis review)	Zeolite/graphene oxide composites synthesis review	Future perspectives/applications	Discusses advanced material development (not a direct hydroponic study).
[45]	Kim et al., 2023	Review Article	N/A (Material science review)	2D MOFs and zeolites for composite membranes	Review of material properties/applications	Focuses on gas separation and material science (not direct hydroponics).
[46]	Zhao et al., 2024	Review Article	N/A (Material science review)	Synthesis and photoelectrocatalysis of zeolite-based composites	Review of advanced material properties	Focuses on catalytic properties of novel zeolite composites.
[47]	Doszhanov et al., 2024	Experimental Study (Soil/Lab)	Parsley (*Petroselinum crispum*)	Organic I and Se fertilizer based on biochar	Biofortification levels, plant growth	Developed a new slow-release fertilizer for soil application.
[48]	Lesbayev et al., 2024	Experimental Study	N/A (Material synthesis)	Preparation of nanoporous carbon from rice husk	Textural characteristics, hydrogen sorption capacity	Focused on material science; creating high-quality sorbent material.

Table A1. *Cont.*

Ref. No	Study ID (Citation, Year)	Study Type/Design	System/Plant Model	Intervention/Exposure Details	Key Outcomes Measured	Relevant Findings (Summary)
[49]	Mansurov et al., 2022	Experimental Study	N/A (Material science)	Modified carbon sorbents based on walnut shell	Sorption of toxic gases	Focused on gas phase environmental remediation (not water/hydroponics).
[50]	Sanchez et al., 2025	Experimental Study	Lettuce (Hydroponic and Soil systems)	Walnut shell biochar and fertilizer application	Yield, nutrient uptake, plant growth parameters	Direct comparison showing influence of biochar on yield in both systems.
[51]	Zhang et al., 2021	Experimental Study	N/A (Water treatment study)	Magnetic activated carbon for heavy metal adsorption	Adsorption efficiency Pb(II) and Cd(II), mechanism	Lab study characterizing novel magnetic sorbent performance.
[52]	Rahman et al., 2014	Experimental Study	N/A (Water treatment study)	Acid activated carbons from oil palm and coconut shells	Heavy metal removal efficiency	Lab study comparing activation methods and removal capacities.
[53]	Asaduzzaman & Asao, 2020	Review/Experimental Study	Strawberry in recycled hydroponics	Autotoxicity mitigation methods (e.g., activated carbon)	Plant growth, accumulation of allelochemicals	Identified causes and solutions for autotoxicity in closed-loop systems.
[54]	Qiu et al., 2022	Experimental Study	N/A (Water treatment study)	Activated carbon adsorption of heavy metals in presence of NOM	Adsorption efficiency, regeneration methods	Investigated the influence of natural organic matter on heavy metal removal.
[55]	Foo & Hameed, 2010	Review Article (Theoretical)	N/A	Review of adsorption isotherm modeling systems	Modeling approaches	Theoretical paper focusing on mathematical models of adsorption.
[56]	Jones et al., 2009	Review Article (Conceptual)	N/A (Soil/Plant biology context)	Review of carbon flow in the rhizosphere	Root exudate mechanisms	Foundational review on plant–soil interactions (soil focus).
[57]	Bertin et al., 2003	Review Article (Conceptual)	N/A (Plant biology context)	Role of root exudates and allelochemicals	Mechanisms of allelopathy	Foundational review on chemical signaling and allelopathy.
[58]	Badri & Vivanco, 2009	Review Article (Conceptual)	N/A (Plant biology context)	Regulation and function of root exudates	Genetic/biological regulation	Foundational review on biological control of exudation.

Table A1. *Cont.*

Ref. No	Study ID (Citation, Year)	Study Type/Design	System/Plant Model	Intervention/Exposure Details	Key Outcomes Measured	Relevant Findings (Summary)
[59]	Rivera-Utrilla et al., 2013	Review Article	N/A (Environmental context)	Pharmaceuticals as emerging contaminants and removal methods	Review of contamination and treatment technologies	General review on pharmaceutical pollution (not specific to hydroponics).
[60]	Nam et al., 2014	Experimental Study	N/A (Water treatment study)	Activated carbon adsorption of micropollutants	Adsorption characteristics	Study on removing trace organic contaminants using activated carbon.
[61]	Sevilla & Fuertes, 2009	Experimental Study	N/A (Material science)	Hydrothermal carbonization of saccharides	Material properties, porosity	Study focused on synthesis of carbon materials.
[62]	Yang & Xing, 2010	Theoretical/Review	N/A (Theoretical context)	Adsorption of organic compounds by carbon nanomaterials	Polanyi theory application, modeling	Theoretical paper applying Polanyi theory to carbon nanomaterial adsorption modeling.
[63]	Rivera-Utrilla et al., 2011	Review Article	N/A	Activated carbon modifications for water treatment	Review of modification techniques	Overview of chemical and physical modifications to enhance AC performance.
[64]	Foo & Hameed, 2010	Review Article	N/A	Review of dye removal via activated carbon adsorption	Adsorption efficiency, mechanisms	Comprehensive review focusing on using AC for textile dye removal.
[65]	El Gamal. et al., 2018	Review Article	N/A	Bio-regeneration of activated carbon	Review of regeneration methods	Overview of biological methods for restoring AC capacity.
[66]	León et al., 2020	Design/Cost Analysis	N/A (Industrial process design)	Production of AC from waste nutshells (physical activation)	Design parameters, cost estimation	Engineering study on the industrial production of AC.
[67]	Ahmad et al., 2014	Review Article	N/A (Environmental context)	Biochar as a sorbent for contaminant management	Review of application in soil/water	Overview of biochar use for remediation of various pollutants.
[6]	Bindra et al., 2023	Experimental Study (Lab/Pot)	Tomato plant	Zeolite/MOF composite for targeted nutrient release	Nutrient release profile, plant uptake	Developed a smart fertilizer using composite materials.

Table A1. *Cont.*

Ref. No	Study ID (Citation, Year)	Study Type/Design	System/Plant Model	Intervention/Exposure Details	Key Outcomes Measured	Relevant Findings (Summary)
[68]	Safarpour & Khataee, 2019	Book Chapter/Review	N/A (Material science context)	Graphene-based materials for water purification	Material properties, purification efficiency	Overview of graphene applications in water treatment.
[69]	Liu et al., 2017	Experimental Study	N/A (Material science)	Preparation of graphene/zeolite composites	Adsorption of pollutants (dyes) in water	Developed a composite material and tested its pollutant adsorption capacity.
[70]	Seitzhanova et al., 2024	Experimental Study	N/A (Material synthesis/desalination)	Graphene membranes from rice husk waste	Desalination efficiency	Study focused on membrane technology for water desalination.
[71]	Ong et al., 2016	Review Article	N/A (Material science/catalysis)	Graphitic carbon nitride (g-C3N4) photocatalysts	Catalytic properties, sustainability applications	Review focused on advanced catalytic materials.
[72]	Hua et al., 2023	Experimental Study (Lab/Sensor Dev)	N/A (Biosensor development)	3D graphene oxide–CNT composite electrochemical sensor	Ammonium detection limit/sensitivity	Developed a new sensor for detecting ammonium in human sweat.
[73]	Horcajada et al., 2006	Review Article	N/A (Biomedical context)	Metal–Organic Frameworks (MOFs) for drug delivery	Drug delivery efficacy	Review focused on biomedical applications of MOFs.
[74]	Li et al., 2009	Review Article	N/A (Material science context)	MOFs for selective gas adsorption and separation	Gas separation efficiency	Review focused on industrial gas separation using MOFs.
[75]	Khan et al., 2013	Review Article	N/A (Environmental context)	MOFs for removal of hazardous materials from water	Review of adsorption mechanisms	Overview of using MOFs for water remediation.
[76]	Cui et al., 2016	Review Article	N/A (Material science context)	MOFs as platforms for functional materials	Material synthesis and applications	General review of MOF material science.
[77]	Mohammad, H.S et al., 2022	Review Article	N/A (Environmental context)	Carbon-Based Materials for Adsorption of Organic Pollutants	Review of recent advances	Overview of various carbon materials for environmental remediation.
[78]	Hasan & Jhung, 2015	Review Article	N/A (Environmental context)	MOFs for removal of hazardous organics from water	Adsorption mechanisms	Review detailing potential mechanisms for organic pollutant removal using MOFs.

Table A1. *Cont.*

Ref. No	Study ID (Citation, Year)	Study Type/Design	System/Plant Model	Intervention/Exposure Details	Key Outcomes Measured	Relevant Findings (Summary)
[79]	Ding & Wang, 2013	Review Article	N/A (Material science context)	Covalent Organic Frameworks (COFs)	Design principles, applications	General review of COF material science.
[80]	Ahmadijokani et al., 2024	Review Article	N/A (Material science/environmental context)	COF and MOF hybrids for wastewater treatment	Review of performance	Overview of advanced hybrid materials for water treatment applications.
[81]	Hedström, 2001	Review Article	N/A (Water treatment context)	Ion exchange of ammonium in zeolites	Literature review of mechanisms	Foundational review summarizing zeolite performance for ammonium removal.
[82]	Teutli-Sequeira et al., 2009	Experimental Study	N/A (Water treatment study)	Influence of Na^+, Ca^{2+}, Mg^{2+}, NH_4^+ on Cd^{2+} sorption by zeolite	Sorption dynamics of heavy metals	Investigated competitive adsorption dynamics on zeolite materials.
[83]	Rahavi et al., 2024	Experimental Study	Tomato in soilless cultivation (Hydroponic/Perlite)	Activated carbon and K-enriched NanoZeolite	Yield, nutrient content, water use efficiency	Demonstrated improved tomato growth using combined amendments under low-quality water conditions.
[84]	Velásquez-Hernández et al., 2019	Experimental Study	N/A (Material science)	Degradation of ZIF-8 (MOF) in buffered media	Stability in physiological solutions	Studied the stability of a specific MOF (ZIF-8) in biological/aqueous buffers.
[85]	Luzuriaga et al., 2019	Experimental Study	N/A (Material science)	ZIF-8 degradation in cell media, serum, and buffers	Material stability analysis	Confirmed the degradation of ZIF-8 in certain application contexts.
[86]	Wang et al., 2015	Experimental Study	N/A (Water treatment study)	Zirconium MOF UiO-66 for arsenic removal	Arsenic removal efficiency	Demonstrated high efficiency of a specific MOF for removing heavy metals.
[87]	Lin et al., 2024	Experimental Study	N/A (Water treatment study)	Alginate/UiO-66-NH2 nanocomposite	Phosphate removal efficiency	Developed a novel composite for nutrient/pollutant sequestration.

Table A1. *Cont.*

Ref. No	Study ID (Citation, Year)	Study Type/Design	System/Plant Model	Intervention/Exposure Details	Key Outcomes Measured	Relevant Findings (Summary)
[88]	Ghaffari et al., 2019	Experimental Study	N/A (Catalysis study)	Fe-loaded zeolites and silica for phenol degradation	Catalytic degradation efficiency	Study focused on catalytic breakdown of organic pollutants.
[89]	Wu et al., 2024	Experimental Study	N/A (Catalysis study)	Mn3O4 catalysts for oxidation of phenolic contaminants	Catalytic oxidation efficiency	Study focused on advanced oxidation processes for water treatment.
[90]	Hosseinzadeh et al., 2017	Experimental Study	Closed Hydroponic System (Tomato)	Comparison of GAC, ion exchange, and ozonation processes	Water quality parameters, nutrient reuse feasibility	GAC and ion exchange were effective treatments for water reuse in closed systems.
[91]	Hosseinzadeh et al., 2019	Experimental Study	Closed Hydroponic System	UV/H_2O_2 advanced oxidation process	Degradation kinetics of root exudates, cost analysis	UV/H_2O_2 effectively degraded organic pollutants, ensuring water quality for reuse.
[92]	Shah et al., 2015	Experimental Study	N/A (Water treatment study)	Iron-impregnated activated carbon adsorbent	Methylene blue removal, regeneration efficiency	Developed an effective modified AC material for dye removal.
[93]	Xu et al., 2022	Experimental Study	N/A (Environmental remediation)	Electroactive Fe-biochar for remediation	Removal efficiency of arsenic and chromium	Focused on using biochar in redox-related soil/water remediation strategies.
[94]	Okpara et al., 2025	Review Article	N/A (Material science review)	Copper-carbon nanostructured heterojunctions	Pollutant removal mechanisms	Review of advanced material science in water purification.
[95]	Alam et al., 2021	Experimental Study	N/A (Water treatment study)	Pd–Ni nanoparticles supported on activated carbon	Basic blue 3 dye removal efficiency	Developed modified AC for efficient dye removal.
[96]	Seo et al., 2025	Experimental Study	N/A (Water treatment study)	Iron-modified activated carbon application	Phosphate removal efficiency	Study focused on targeted removal of phosphate using modified AC.
[97]	Biliani et al., 2025	Experimental Study	N/A (Water treatment study)	Zeolites of different origin	Eutrophication control (N, P removal) from freshwater	Compared natural zeolites for effectiveness in nutrient management.

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Ref. No	Study ID (Citation, Year)	Study Type/Design	System/Plant Model	Intervention/Exposure Details	Key Outcomes Measured	Relevant Findings (Summary)
[99]	Król, 2020	Review Article	N/A (Material science review)	Natural vs. Synthetic Zeolites	Material properties, applications	Comparative review of natural and synthesized zeolite materials.
[101]	Saleem et al., 2025	Life Cycle Assessment	N/A (Industrial assessment)	High-value activated carbon production	Environmental impact, LCA metrics	Engineering/sustainability study on AC production impacts.
[98]	Wang et al., 2024	Review Article	N/A (Review of AC technology)	Deactivation mechanisms and regeneration methods of AC	Review of industrial practices	Overview of practical challenges and solutions in AC use.
[100]	Mondal. et al., 2021	Review Article	N/A (Soil context review)	Zeolites enhance soil health, crop productivity	Review of agricultural application (soil-based)	Discusses benefits of zeolites primarily in traditional agriculture.
[102]	Chen et al., 2024	Environmental Assessment	N/A (Material science/synthesis)	Zeolites synthesized from chemicals vs. natural minerals	Environmental impact, Green Chemistry metrics	Comparative life cycle assessment of different zeolite production methods.

References

1. Chatzigeorgiou, I.; Liantas, G.; Spanos, P.; Gkriniari, V.; Maloupa, E.; Ntinas, G.K. Hydroponic Cultivation of Vine Leaves with Reduced Carbon Footprint in a Mediterranean Greenhouse. *Sustainability* **2022**, *14*, 8011. [CrossRef]
2. Li, X.; Zhou, J.; Tang, Y.; Li, Y.; Jin, Z.; Kong, H.; Zhao, M.; Zheng, X.; Bei, K. A hydroponic vertical greening system for disposal and utilization of pre-treated Blackwater: Optimization of the operating conditions. *Ecol. Eng.* **2022**, *183*, 106739. [CrossRef]
3. Awad, Y.; Lee, S.-E.; Vu, N.T.; Farooq, M.; Kim, S.; Kim, H.S.; Vithanage, M.; Usman, A.; Al-Wabel, M.; Meers, E.; et al. Biochar, a potential hydroponic growth substrate, enhances the nutritional status and growth of leafy vegetables. *J. Clean. Prod.* **2017**, *156*, 581–588. [CrossRef]
4. Dyer, A. Ion exchange capacity. In *Verified Syntheses of Zeolitic Materials*; Elsevier Science: Amsterdam, The Netherlands, 2001; pp. 67–68. [CrossRef]
5. Sambo, P.; Nicoletto, C.; Giro, A.; Pii, Y.; Valentinuzzi, F.; Mimmo, T.; Lugli, P.; Orzes, G.; Mazzetto, F.; Astolfi, S.; et al. Hydroponic solutions for soilless production systems: Issues and opportunities in a smart agriculture perspective. *Front. Plant Sci.* **2019**, *10*, 923. [CrossRef]
6. Bindra, P.; Sharma, S.; Sahu, B.K.; Bagdwal, H.; Shanmugam, V.; Singh, M. Targeted nutrient application to tomato plant with MOF/Zeolite composite wrapped with stimuli-responsive biopolymer. *Mater. Today Commun.* **2023**, *34*, 105264. [CrossRef]
7. Mussina, A.; Baitasheva, G.; Rakhimova, Z.; Raimbekova, B.; Gubasheva, B.E.; Medeuova, G.; Baymurzina, Z.; Tynyshbek, D. Evaluation of tree species Aésculus hippocastanum as a phytoremediator in conditions of artificial soil contamination. *Casp. J. Environ. Sci.* **2025**, *23*, 707–720. [CrossRef]
8. Mosa, A.; El-Banna, M.F.; Gao, B. Biochar filters reduced the toxic effects of nickel on tomato (*Lycopersicon esculentum* L.) grown in nutrient film technique hydroponic system. *Chemosphere* **2019**, *149*, 254–262. [CrossRef]
9. Olasehinde, A.A. Biodegradable Growth Media Alternatives for Sustainable Hydroponic Farming. *Curr. J. Appl. Sci. Technol.* **2025**, *44*, 147–152. [CrossRef]
10. Calabria, J.L.; Lens, P.N.; Yeh, D.H. Zeolite ion exchange to facilitate anaerobic membrane bioreactor wastewater nitrogen recovery and reuse for lettuce fertigation in vertical hydroponic systems. *Environ. Eng. Sci.* **2019**, *36*, 690–698. [CrossRef]
11. El-Shal, R.M.; El-Naggar, A.H.; El-Beshbeshy, T.R.; Mahmoud, E.K.; El-Kader, N.I.A.; Missaui, A.M.; Du, D.; Ghoneim, A.M.; El-Sharkawy, M.S. Effect of Nano-Fertilizers on Alfalfa Plants Grown under Different Salt Stresses in Hydroponic System. *Agriculture* **2022**, *12*, 1113. [CrossRef]
12. Pan, W.L.; Madsen, I.J.; Bolton, R.P.; Graves, L.; Sistrunk, T. Ammonia/ammonium toxicity root symptoms induced by inorganic and organic fertilizers and placement. *Agron. J.* **2016**, *108*, 2485–2492. [CrossRef]
13. Nurbaity, A.; Istifadah, N.; Haryantini, B.A.; Ilhami, M.F.; Habibullah, M.I.; Arifin, M. Optimization of hydroponic technology for production of mycorrhiza biofertilizer. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *347*, 012017. [CrossRef]
14. Vehar, A.; Marsic, N.K.; Železnikar, Š.; Potočnik, D.; Strojnik, L.; Petkovšek, M.M.; Šircelj, H.; Kastelec, D.; Kovačič, A.; Pintar, M.; et al. Influence of contaminants of emerging concern on the primary and secondary metabolites of hydroponically grown tomatoes. *Food Chem.* **2025**, *491*, 145226. [CrossRef] [PubMed]
15. Li, J.; Ullah, R.; Jiao, J.; Sun, J.; Bai, S. Ion exchange of cations from different groups with ammonium-modified clinoptilolite and selectivity for methane and nitrogen. *Mater. Chem. Phys.* **2020**, *256*, 123760. [CrossRef]
16. Korotta-Gamage, S.M.; Sathasivan, A. Potential of a biologically activated carbon treatment to remove organic carbon from surface waters. *Int. Biodeterior. Biodegrad.* **2017**, *124*, 82–90. [CrossRef]
17. Yang, X.; Fan, J.; Ge, J.; Luo, Z. Effect of irrigation with activated water on root morphology of hydroponic rice and wheat seedlings. *Agronomy* **2022**, *12*, 1068. [CrossRef]
18. Suryaningtyas, D.T.; Fatiha, Y.G.N.; Oktariani, P. Zeoponic, a plant growing medium from zeolite mineral. *IOP Conf. Ser. Earth Environ. Sci.* **2023**, *1133*, 012020. [CrossRef]
19. Zahid, M.; Doszhanov, Y.; Saurykova, K.; Ahmadi, N.; Bolatova, D.; Kurmanbayeva, M.; Aydarbek, A.; Ihsas, R.; Seitzhanova, M.; Akhmetzhanova, D.; et al. Modification and Application of Natural Clinoptilolite and Mordenite from Almaty Region for Drinking Water Purification. *Molecules* **2021**, *30*, 2021. [CrossRef]
20. Rashed, M.N.; Palanisamy, P.N. Introductory chapter: Adsorption and ion exchange properties of zeolites for treatment of polluted water. In *Zeolites and Their Applications*; IntechOpen: London, UK, 2018. [CrossRef]
21. Adam, M.R.; Othman, M.H.D.; Hubadillah, S.K.; Abd Aziz, M.H.; Jamalludin, M.R. Application of natural zeolite clinoptilolite for the removal of ammonia in wastewater. *Mater. Today Proc.* **2025**, *in press*. [CrossRef]
22. Fuentes-Peñailillo, F.; Gutter, K.; Vega, R.; Silva, G.C. New Generation Sustainable Technologies for Soilless Vegetable Production. *Horticulturae* **2024**, *10*, 49. [CrossRef]
23. Wang, S.; Kleiner, Y.; Clark, S.M.; Raghavan, V.; Tartakovsky, B. Review of current hydroponic food production practices and the potential role of bioelectrochemical systems. *Rev. Environ. Sci. Biotechnol.* **2024**, *23*, 897–921. [CrossRef]

24. Pérez-Botella, E.; Valencia, S.; Rey, F. Zeolites in Adsorption Processes: State of the Art and Future Prospects. *Chem. Rev.* **2022**, *122*, 17647–17695. [CrossRef]
25. Van, Q.N.; Van, H.T.; Le, S.H.; Nguyen, T.H.; Nguyen, H.T.; Pham, Q.T.; Nguyen, T.T.; Tran, T.N.H.; Nguyen, T.B.H.; Hoang, T.K. Production of hydroponic solution from human urine using adsorption–desorption method with coconut shell-derived activated carbon. *Environ. Technol. Innov.* **2021**, *23*, 101708. [CrossRef]
26. Page, M.J.; McKenzie, J.E.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; Shamseer, M.; Tetzlaff, J.M.; Akl, E.A.; Brennan, S.E.; et al. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ* **2021**, *372*, n71. [CrossRef]
27. Seitzhanova, M.A.; Doszhanov Ye, O.; Kuldeev, E.I.; Mansurov, Z.A.; Taju, K.; Tanirbergenova, S.K.; Tazhkenova, G.K. Influence of heat treatment on the sorption characteristics of zeolite used in water purification. *Combust. Plasma Chem.* **2023**, *21*, 173–179. (In Russian) [CrossRef]
28. Mansouri, N.; Rikhtegar, N.; Panahi, H.A.; Atabi, F.; Shahraki, B.K. Porosity, characterization and structural properties of natural zeolite-clinoptilolite-as a sorbent. *Environ. Prot. Eng.* **2013**, *39*, 139–152. [CrossRef]
29. Elshorbagy, W.; Chowdhury, R. (Eds.) *Water Treatment*; IntechOpen: London, UK, 2013. [CrossRef]
30. Kenzhaliyev, B.K.; Surkova, T.Y.; Berkinbayeva, A.N.; Dosymbayeva, Z.D.; Abdikerim, B.E. Revisiting the Kazakhstan natural sorbents modification. *Metalurgija* **2020**, *59*, 117–120.
31. Wasielewski, S.; Rott, E.; Minke, R.; Steinmetz, H. Application of natural clinoptilolite for ammonium removal from sludge water. *Molecules* **2020**, *26*, 114. [CrossRef]
32. Cheng, Z.; Ding, W. Ammonium removal from water by natural and modified zeolite: Kinetic, equilibrium, and thermodynamic studies. *Desalination Water Treat.* **2015**, *55*, 978–985. [CrossRef]
33. Nogueira, H.P.; Toma, S.H.; Silveira, A.T., Jr.; Araki, K. Zeolite-SPION nanocomposite for ammonium and heavy metals removal from wastewater. *J. Braz. Chem. Soc.* **2025**, *31*, 2342–2350. [CrossRef]
34. Rahmani, A.R.; Samadi, M.T.; Ehsani, H.R. Investigation of clinoptilolite natural zeolite regeneration by air stripping followed by ion exchange for removal of ammonium from aqueous solutions. *J. Environ. Health Sci. Eng.* **2009**, *6*, 167–172.
35. Ofiera, L.M.; Kazner, C. Influence of Ammonium on the Adsorption and Desorption of Heavy Metals in Natural Zeolites. *Processes* **2025**, *13*, 2647. [CrossRef]
36. Murkani, M.; Nasrollahi, M.; Ravanbakhsh, M.; Bahrami, P.; Jaafarzadeh Haghighi Fard, N. Evaluation of natural zeolite clinoptilolite efficiency for the removal of ammonium and nitrate from aquatic solutions. *Environ. Health Eng. Manag. J.* **2015**, *2*, 17–22.
37. Nakano, T.; Thi Hanh, D.; Owaki, A.; Nozue, Y.; Nam, N.H.; Araki, S. Insulator-to-metal transition and magnetism of potassium metals loaded into regular cages of zeolite LSX. *J. Korean Phys. Soc.* **2013**, *63*, 512–516. [CrossRef]
38. Velarde, L.; Nabavi, M.S.; Escalera, E.; Antti, M.L.; Akhtar, F. Adsorption of heavy metals on natural zeolites: A review. *Chemosphere* **2023**, *328*, 138508. [CrossRef] [PubMed]
39. Montégut, G.; Michelin, L.; Brendlé, J.; Lebeau, B.; Patarin, J. Ammonium and potassium removal from swine liquid manure using clinoptilolite, chabazite and faujasite zeolites. *J. Environ. Manag.* **2016**, *167*, 147–155. [CrossRef] [PubMed]
40. Halimoon, N.; Yin, R.G.S. Removal of heavy metals from textile wastewater using zeolite. *Environ. Asia* **2010**, *3*, 124–130.
41. He, K.; Chen, Y.; Tang, Z.; Hu, Y. Removal of heavy metal ions from aqueous solution by zeolite synthesized from fly ash. *Environ. Sci. Pollut. Res.* **2016**, *23*, 2778–2788. [CrossRef]
42. Castro, C.J.; Shyu, H.Y.; Xaba, L.; Bair, R.; Yeh, D.H. Performance and onsite regeneration of natural zeolite for ammonium removal in a field-scale non-sewered sanitation system. *Sci. Total Environ.* **2021**, *776*, 145938. [CrossRef]
43. Guida, S.; Potter, C.; Jefferson, B.; Soares, A. Preparation and evaluation of zeolites for ammonium removal from municipal wastewater through ion exchange process. *Sci. Rep.* **2020**, *10*, 12426. [CrossRef]
44. Subramanian, N.; Perumal, T.; Mangesh, V.L.; Chinnadurai, R.; Sakthinathan, S.; Chiu, T.; Selvaraj, M.; Madhavan, J. Future perspectives on zeolite/graphene oxide composite synthesis and applications. *Energy Fuels* **2023**, *37*, 17013–17051. [CrossRef]
45. Kim, M.; Choi, W.; Lee, C.H.; Kim, D. 2D MOFs and zeolites for composite membrane and gas separation applications: A brief review. *ACS Mater.* **2023**, *4*, 148–161. [CrossRef] [PubMed]
46. Zhao, Y.; Liu, M.; Guo, Y.; Wu, Z. Recent Advances in the Synthesis and Photoelectrocatalysis of Zeolite-Based Composites. *Catalysts* **2024**, *14*, 938. [CrossRef]
47. Doszhanov, Y.; Atamanov, M.; Jandosov, J.; Saurykova, K.; Bassygarayev, Z.; Orazbayev, A.; Turganbay, S.; Sabitov, A. Preparation of Granular Organic Iodine and Selenium Complex Fertilizer Based on Biochar for Biofortification of Parsley. *Scientifica* **2024**, *2024*, 6601899. [CrossRef]

48. Lesbayev, B.; Rakhymzhan, N.; Ustayeva, G.; Maral, Y.; Atamanov, M.; Auyelkhankyzy, M.; Zhamash, A. Preparation of-Nanoporous Carbon from Rice Husk with Improved Textural Characteristics for Hydrogen Sorption. *J. Compos. Sci.* **2024**, *8*, 74. [CrossRef]
49. Mansurov, Z.A.; Velasco, L.F.; Lodewyckx, P.; Doszhanov, E.O.; Azat, S. Modified carbon sorbents based on walnut shell for sorption of toxic gases. *J. Eng. Phys. Thermophys.* **2022**, *95*, 1383–1392. [CrossRef]
50. Sanchez, E.; Zabaleta, R.; Navas, A.L.; Maldonado, V.N.F.; Fabani, M.P.; Mazza, G.; Rodriguez, R. Influence of Walnut Shell Biochar and Fertilizer on Lettuce Production in Hydroponic and Conventional Systems. *Agronomy* **2025**, *15*, 658. [CrossRef]
51. Zhang, Z.; Wang, T.; Zhang, H.; Liu, Y.; Xing, B. Adsorption of Pb(II) and Cd(II) by magnetic activated carbon and its mechanism. *Sci. Total Environ.* **2021**, *757*, 143910. [CrossRef]
52. Rahman, M.M.; Adil, M.; Yusof, A.M.; Kamaruzzaman, Y.B.; Ansary, R.H. Removal of heavy metal ions with acid activated carbons derived from oil palm and coconut shells. *Materials* **2014**, *7*, 3634–3650. [CrossRef]
53. Asaduzzaman, M.; Asao, T. Autotoxicity in strawberry under recycled hydroponics and its mitigation methods. *Hortic. J.* **2020**, *89*, 124–137. [CrossRef]
54. Qiu, L.; Suo Ch Zhang, N.; Yuan, R.; Chen, H.; Zhou, B. Adsorption of heavy metals by activated carbon: Effect of natural organic matter and regeneration methods of the adsorbent. *Desalination Water Treat.* **2022**, *252*, 148–166. [CrossRef]
55. Foo, K.Y.; Hameed, B.H. Insights into the modeling of adsorption isotherm systems. *Chem. Eng. J.* **2010**, *156*, 2–10. [CrossRef]
56. Jones, D.L.; Nguyen, C.; Finlay, R.D. Carbon flow in the rhizosphere: Carbon trading at the soil–root interface. *Plant Soil* **2009**, *321*, 5–33. [CrossRef]
57. Bertin, C.; Yang, X.; Weston, L.A. The role of root exudates and allelochemicals in the rhizosphere. *Plant Soil* **2003**, *256*, 67–83. [CrossRef]
58. Badri, D.V.; Vivanco, J.M. Regulation and function of root exudates. *Plant Cell Environ.* **2009**, *32*, 666–681. [CrossRef] [PubMed]
59. Rivera-Utrilla, J.; Sánchez-Polo, M.; Ferro-García, M.A.; Prados-Joya, G.; Ocampo-Pérez, R. Pharmaceuticals as emerging contaminants and their removal from water. *Chemosphere* **2013**, *93*, 1268–1287. [CrossRef]
60. Nam, S.W.; Cho, H.H.; Han, J.; Her, N.; Yoon, Y. Adsorption characteristics of selected hydrophilic and hydrophobic micropollutants in water using activated carbon. *J. Hazard. Mater.* **2014**, *270*, 144–152. [CrossRef]
61. Sevilla, M.; Fuertes, A.B. Chemical and structural properties of carbonaceous products obtained by hydrothermal carbonization of saccharides. *Chem. Eur. J.* **2009**, *15*, 4195–4203. [CrossRef]
62. Yang, K.; Xing, B. Adsorption of organic compounds by carbon nanomaterials in aqueous phase: Polanyi theory and its application. *Chemosphere* **2010**, *79*, 681–688. [CrossRef]
63. Rivera-Utrilla, J.; Sánchez-Polo, M.; Gómez-Serrano, V.; Álvarez, P.M.; Alvim-Ferraz, M.C.M.; Dias, J.M. Activated carbon modifications to enhance its water treatment applications. An overview. *J. Hazard. Mater.* **2011**, *187*, 1–23. [CrossRef]
64. Foo, K.Y.; Hameed, B.H. An overview of dye removal via activated carbon adsorption process. *Desalination Water Treat.* **2010**, *19*, 255–274. [CrossRef]
65. El Gamal, M.; Mousa, H.A.; El-Naas, M.H.; Zacharia, R.; Judd, S. Bio-regeneration of activated carbon: A comprehensive review. *Sep. Purif. Technol.* **2018**, *197*, 345–359. [CrossRef]
66. León, M.; Silva, J.; Carrasco, S.; Barrientos, N. Design, cost estimation and sensitivity analysis for a production process of activated carbon from waste nutshells by physical activation. *Processes* **2020**, *8*, 945. [CrossRef]
67. Ahmad, M.; Rajapaksha, A.U.; Lim, J.; Zhang, M.; Bolan, N.; Mohan, D.; Vithanage, M.; Lee, S.; Ok, Y. Biochar as a sorbent for contaminant management in soil and water: A review. *Chemosphere* **2014**, *99*, 19–33. [CrossRef]
68. Safarpour, M.; Khataee, A. Graphene-based materials for water purification. In *Nanoscale Materials in Water Purification*; Elsevier: Amsterdam, The Netherlands, 2019; pp. 383–430. [CrossRef]
69. Liu, H.; Yu, A.; Liu, H.; Chu, S.; Tan, S. Preparation of graphene/zeolite composites and the adsorption of pollutants in water. *Russ. J. Appl. Chem.* **2017**, *90*, 1171–1180. [CrossRef]
70. Seitzhanova, M.; Azat, S.; Yeleuov, M.; Taurbekov, A.; Mansurov, Z.; Doszhanov, E.; Berndtsson, R. Production of graphene membranes from rice husk biomass waste for improved desalination. *Nanomaterials* **2024**, *14*, 224. [CrossRef]
71. Ong, W.J.; Tan, L.; Ng, Y.; Yong, S.; Chai, S. Graphitic carbon nitride (g-C_3N_4)-based photocatalysts for artificial photosynthesis and environmental remediation: Are we a step closer to achieving sustainability. *Chem. Rev.* **2016**, *116*, 7159–7329. [CrossRef]
72. Hua, Y.; Guan, M.; Xia, L.; Chen, Y.; Mai, J.; Zhao, C.; Liao, C. Highly stretchable and robust electrochemical sensor based on 3D graphene oxide–CNT composite for detecting ammonium in sweat. *Biosensors* **2023**, *13*, 409. [CrossRef]
73. Horcajada, P.; Serre, C.; Vallet-Regí, M.; Sebban, M.; Taulelle, F.; Férey, G. Metal–Organic Frameworks as Advanced Materials for Drug Delivery. *Angew. Chem. Int. Ed.* **2006**, *45*, 5974–5978. [CrossRef]

74. Li, J.-R.; Kuppler, R.J.; Zhou, H.-C. Selective Gas Adsorption and Separation in Metal–Organic Frameworks. *Chem. Soc. Rev.* **2009**, *38*, 1477–1504. [CrossRef]
75. Khan, N.A.; Hasan, Z.; Jhung, S.H. Adsorptive Removal of Hazardous Materials Using Metal–Organic Frameworks (MOFs): A Review. *J. Hazard. Mater.* **2013**, *244–245*, 444–456. [CrossRef] [PubMed]
76. Cui, Y.; Li, B.; He, H.; Zhou, W.; Chen, B.; Qian, G. Metal–organic frameworks as platforms for functional materials. *Acc. Chem. Res.* **2016**, *49*, 483–493. [CrossRef] [PubMed]
77. Mohammad, H.S.; Maryam, A.T.; Toraj, M. One-dimensional graphene for efficient aqueous heavy metal adsorption: Rapid removal of arsenic and mercury ions by graphene oxide nanoribbons (GONRs). *Chemosphere* **2020**, *253*, 126647. [CrossRef]
78. Hasan, Z.; Jhung, S.H. Removal of Hazardous Organics from Water Using Metal–Organic Frameworks (MOFs): Plausible Mechanisms for Selective Adsorptions. *J. Hazard. Mater.* **2015**, *283*, 329–339. [CrossRef] [PubMed]
79. Ding, S.-Y.; Wang, W. Covalent Organic Frameworks (COFs): From Design to Applications. *Chem. Soc. Rev.* **2013**, *42*, 548–568. [CrossRef]
80. Ahmadijokani, F.; Ghaffarkhah, A.; Molavi, H.; Dutta, S.; Lu, Y.; Wuttke, S.; Kamkar, M.; Rojas, O.J.; Arjmand, M. COF and MOF hybrids: Advanced materials for wastewater treatment. *Adv. Funct. Mater.* **2024**, *34*, 2305527. [CrossRef]
81. Hedström, A. Ion exchange of ammonium in zeolites: A literature review. *Water Res.* **2001**, *35*, 1599–1610. [CrossRef]
82. Teutli-Sequeira, A.; Solache-Ríos, M.; Olguín, M.T. Influence of Na^+, Ca^{2+}, Mg^{2+} and NH_4^+ on sorption of Cd^{2+} by zeolitic material. *Hydrometallurgy* **2009**, *97*, 46–52. [CrossRef]
83. Rahavi, A.; Shahriari, M.H.; Hedayat, M.; Dindarlou, A. Application of activated carbon and Potassium Enriched NanoZeolite on tomato in soilless cultivation under the conditions of using low quality water. *Iran. Water Res. J.* **2024**, *18*.
84. Velásquez-Hernández, M.J.; Ricco, R.; Carraro, F.; Limpoco, F.T.; Linares-Moreau, M.; Leitner, E.; Wiltsche, H.; Rattenberger, J.; Schröttner, H.; Frühwirt, P.; et al. Degradation of ZIF-8 in phosphate buffered saline media. *CrystEngComm* **2019**, *21*, 4538–4544. [CrossRef]
85. Luzuriaga, M.A.; Benjamin, C.E.; Gaertner, M.W.; Lee, H.; Herbert, F.C.; Mallick, S.; Gassensmith, J.J. ZIF-8 degrades in cell media, serum, and some—But not all—Buffers. *ACS Appl. Mater. Interfaces* **2019**, *11*, 10119–10126. [CrossRef]
86. Wang, C.; Liu, X.; Chen, J.P.; Li, K. Superior removal of arsenic from water with zirconium MOF UiO-66. *Sci. Rep.* **2015**, *5*, 16613. [CrossRef]
87. Lin, X.; Xiong, Y.; Dong, F. Sodium Alginate/UiO-66-NH_2 Nanocomposite for Phosphate Removal. *Nanomaterials* **2024**, *14*, 1176. [CrossRef] [PubMed]
88. Ghaffari, Y.; Gupta, N.K.; Bae, J.; Kim, K.S. Heterogeneous catalytic performance and stability of iron-loaded ZSM-5, zeolite-A, and silica for phenol degradation: A microscopic and spectroscopic approach. *Catalysts* **2019**, *9*, 859. [CrossRef]
89. Wu, W.; Yi, H.; Tang, X.; Kadja, G.T.M.; Zhao, S.; Zhang, Y.; Meng, F.; Sun, L.; Yao, Y.; Niu, Z.; et al. Review on Mn/zeolite: Active species, influence factors and application in air pollution control. *Chem. Eng. J.* **2024**, *497*, 154940. [CrossRef]
90. Hosseinzadeh, S.; Bonarrigo, G.; Verheust, Y.; Roccaro, P.; Van Hulle, S. Water reuse in closed hydroponic systems: Comparison of GAC adsorption, ion exchange and ozonation processes to treat recycled nutrient solution. *Aquac. Eng.* **2017**, *78*, 190–195. [CrossRef]
91. Hosseinzadeh, S.; Testai, D.; Bkheet, M.; De Graeve, J.; Roccaro, P.; Van Hulle, S. Degradation of root exudates in closed hydroponic systems using UV/H_2O_2: Kinetics and cost analysis. *Sci. Total Environ.* **2019**, *687*, 479–487. [CrossRef]
92. Shah, I.; Adnan, R.; Wan Ngah, W.S.; Mohamed, N. Iron impregnated activated carbon as an efficient adsorbent for the removal of methylene blue: Regeneration and kinetics studies. *PLoS ONE* **2015**, *10*, e0122603. [CrossRef]
93. Xu, Z.; Wan, Z.; Sun, Y.; Gao, B.; Hou, D.; Cao, X.; Komárek, M.; Ok, Y.S.; Tsang, D.C. Electroactive Fe-biochar for redox-related remediation of arsenic and chromium: Distinct redox nature with varying iron/carbon speciation. *J. Hazard. Mater.* **2022**, *430*, 128479. [CrossRef]
94. Okpara, E.C.; Quadri, T.W.; Ebenso, E.E.; Rowley-Neale, S.J.; Banks, C.E. Advancing water purification: The role of copper-carbon nanostructured heterojunctions in pollutant removal. *Coord. Chem. Rev.* **2025**, *542*, 216837. [CrossRef]
95. Alam, S.; Khan, M.S.; Umar, A.; Khattak, R.; Zekker, I.; Burlakovs, J.; Ghangrekar, M.M.; Bhowmick, G.D.; Kallistova, A.; Pimenov, N.; et al. Preparation of Pd–Ni nanoparticles supported on activated carbon for efficient removal of basic blue 3 from water. *Water* **2021**, *13*, 1211. [CrossRef]
96. Seo, W.H.; Kim, G.E.; Lee, J.Y.; Choi, S. Application of Iron-Modified Activated Carbon for Phosphate Removal in Aqueous Systems. *Appl. Sci.* **2025**, *15*, 5353. [CrossRef]
97. Król, M. Natural vs. Synthetic Zeolites. *Crystals* **2020**, *10*, 622. [CrossRef]
98. Wang, Y.; Wu, G.; Zhang, Y.; Su, Y.; Zhang, H. The deactivation mechanisms, regeneration methods and devices of activated carbon in applications. *J. Clean. Prod.* **2024**, *476*, 143751. [CrossRef]
99. Biliani, I.; Papadopoulou, E.; Zacharias, I. Evaluating Zeolites of Different Origin for Eutrophication Control of Freshwater Bodies. *Sustainability* **2025**, *17*, 7120. [CrossRef]

100. Mondal, M.; Biswas, B.; Garai, S.; Sarkar, S.; Banerjee, H.; Brahmachari, K.; Bandyopadhyay, P.K.; Maitra, S.; Brestic, M.; Skalicky, M.; et al. Zeolites Enhance Soil Health, Crop Productivity and Environmental Safety. *Agronomy* **2021**, *11*, 448. [CrossRef]
101. Saleem, J.; Khalid Baig Moghal, Z.; Tahir, F.; Al-Ansari, T.; Osman, A.I.; McKay, G. Life cycle assessment of high value activated carbon production based on mass and functional performance metrics. *Sci. Rep.* **2025**, *15*, 32797. [CrossRef]
102. Chen, X.; Xiao, G.; Li, T.; Wang, C.; Cui, Q.; Bao, X.; Yue, Y. Comparative environmental assessment of zeolites synthesized from chemicals and natural minerals. *Green Chem.* **2024**, *26*, 5273–5283. [CrossRef]

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