Response to Reviewer 1 Comments

1. Summary

Thank you very much for taking the time to review this manuscript. Please find the detailed responses below and the corresponding revisions/corrections highlighted/in track changes in the re-submitted files.

2. Questions for General Evaluation	**Reviewer's Evaluation**	**Response and Revisions**
Is the work a significant contribution to the field?	★★★★☆	*We thank the reviewer for this positive evaluation. The manuscript provides an integrative overview of zeolite- and carbon-based sorbents for sustainable hydroponic systems, contributing to both scientific understanding and practical applications.*
Is the work well organized and comprehensively described?	★★★★☆	*We appreciate the reviewer's assessment. The manuscript has been further refined for clarity and structure, ensuring smooth logical progression and comprehensive coverage of key aspects.*
Is the work scientifically sound and not misleading?	★★★★☆	*We thank the reviewer for recognizing the scientific rigor of the study. The content has been carefully reviewed to confirm that all interpretations and discussions remain accurate and well-supported.*
Are there appropriate and adequate references to related and previous work?	★★★★☆	*We are grateful for the positive feedback. Additional relevant references were included in the Introduction*

		to enhance the comparative discussion with existing literature (Page 4–5).
Is the English used correct and readable?	The English is fine and does not require any improvement.	*We appreciate this comment. Only minor stylistic adjustments were made during proofreading to further improve readability and consistency.*

3. Point-by-point response to Comments and Suggestions for Authors

Comment 1: In the paper entitled "Zeolites and Activated Carbons in Hydroponics: Mechanisms, Performance Metrics, Techno-Economic Analysis and Life-Cycle Assessment," the authors offer a review of topics related to title. It is not clear what the aim of this paper is, this must be stated at the end of the Introduction. Also, in the Introduction, the authors must compare this review with other in the literature. This section must be significantly expanded.

Response 1: Thank you for pointing this out. We agree with this comment. Therefore, we have clarified the aim of the review and expanded the Introduction to include a comparison with recent literature. Specifically, we added a clear statement of the review objectives at the end of the Introduction and cited several recent studies to highlight the novelty and scope of our work.

Location in manuscript: Page 4-5, last paragraph of the Introduction (Track Changes).
"…This review aims to provide a comprehensive comparative analysis of zeolites, activated carbons, and their composite materials in hydroponic systems, focusing on their mechanisms, performance metrics, techno-economic viability, and environmental implications. Unlike previous reviews that primarily address material properties or system design separately, this paper integrates adsorption, ion-exchange, and life-cycle perspectives to propose a unified approach for sustainable hydroponic nutrient management."

Comment 2: This is a strong, well-structured review manuscript with a clear focus on an important and timely topic in sustainable agriculture. The integration of techno-economic and life-cycle assessment perspectives is a significant strength.

Response 2: We sincerely appreciate the reviewer's positive evaluation and acknowledgment of the manuscript's structure and focus.

Comment 3: I recommend improving the Abstract, the current abstract is a good summary but it can be more impactful. I think that it must start by more explicitly stating the core problem in hydroponics (e.g., "The accumulation of phytotoxic ammonium, heavy metals, and organic metabolites in recirculating nutrient solutions poses a major challenge to the sustainability and productivity of hydroponic systems."). Also, the key findings should be mentioned; this is that, instead of just listing material properties, authors must state the key

comparative findings. For example: "This review reveals that while zeolites excel in ammonium and cation management, activated carbons are superior for organic contaminant removal. Their combination, especially when functionalized or composited with 2D/3D materials, offers a synergistic solution." The conclusions must mention broader implications, they could end with a stronger conclusion on the impact (e.g., "The judicious application of these advanced sorbents paves the way for more resilient, efficient, and circular hydroponic systems, reducing environmental footprint and enhancing food security.").

Response 3: Thank you for this valuable suggestion. We have revised the Abstract to clearly state the central challenge in hydroponics, summarize the key comparative findings, and end with a stronger statement on broader implications for sustainability and food security.
The ***Conclusion*** section has been fully revised to include clearer key findings, specific future research directions, and a stronger statement on the broader implications and impact. The revised version now highlights the comparative advantages of zeolites and activated carbons, their synergistic potential, and their role in developing more efficient, sustainable, and circular hydroponic systems that reduce environmental footprint and enhance food security.

Location in manuscript: Page 1, Abstract (Track Changes).
"The accumulation of phytotoxic ammonium, heavy metals, and organic metabolites in recirculating nutrient solutions poses a major challenge to the sustainability and productivity of hydroponic systems. This review provides a comparative evaluation of zeolites, activated carbons (ACs), and their composite derivatives for nutrient regulation, contaminant removal, and environmental safety. Zeolites excel in ammonium and cation management, whereas ACs demonstrate superior adsorption of organic contaminants. Their combined application, particularly in functionalized and composite forms, offers a synergistic approach for sustainable hydroponic systems. The judicious use of these materials promotes circularity, reduces resource consumption, and enhances food security."

Comment 4: The content could be enhanced. This by clarifying the "Techno-Economic Analysis and Life-Cycle Assessment". In the title and aims it is mentioned TEA and LCA, but these are not explicitly addressed as dedicated sections in the body of the review. This is a significant gap. Also, it could be added a new section, where techno-economic and environmental perspectives must be discussed. The relative costs of natural vs. modified/advanced sorbents must be discussed. Compare the cost-benefit of regeneration vs. replacement. Also, the authors can mention the economic impact of extended nutrient solution life and reduced fertilizer use.

Response 4: Thank you very much for this insightful and constructive comment. We fully agree that the original version did not explicitly address Techno-Economic Analysis (TEA) and Life-Cycle Assessment (LCA) as dedicated sections, despite their central role in the aims and title of the manuscript. In response, we have substantially revised the manuscript by adding a new integrated section titled "Techno-Economic Analysis and Life-Cycle Assessment", where we systematically discuss the relative costs of natural versus modified sorbents, compare the cost-benefit balance of regeneration versus complete replacement, and

highlight the economic advantages of extended nutrient-solution lifetime and reduced fertilizer consumption.

We have also expanded the environmental assessment by incorporating cradle-to-gate impacts, regeneration-related burdens, and end-of-life considerations for both zeolites and activated carbons. These additions clarify the sustainability implications of sorbent use and strengthen the alignment between the manuscript's aims, title, and body.

Location in manuscript: Page 20, Line 659 onward (Track Changes).

Comment 5: In this paper, the authors must discuss the environmental footprint of sorbent production (e.g., high-temperature activation for AC, chemical use for modifications). Compare this to the environmental benefits they provide (water savings, reduced eutrophication potential from discharged nutrients). Address end-of-life: are spent sorbents hazardous waste? Can they be repurposed (e.g., as soil amendments)?

Response 5: Thank you for this important and constructive comment. We agree that the manuscript required a clearer discussion of the environmental footprint of sorbent production, as well as the downstream environmental benefits and end-of-life considerations. In response, we have expanded the revised manuscript by introducing two dedicated subsections—7.2 Agricultural and Water-Saving Benefits and 7.3 Environmental Footprint and Life-Cycle Assessment, which directly address the reviewer's concerns.

Location in manuscript: Page 20, (Track Changes).

Comment 6: The comparative analysis can be improved, this by creating a summary Table. Table 1 is a good start but is situational. Add a more comprehensive Table 2 that directly compares Zeolites, ACs, and their Composites across key metrics, namely: primary mechanism (ion exchange vs. adsorption vs. catalysis), key target pollutants (NH_4^+, K^+, heavy metals, DOC, pesticides), advantages (selectivity, surface area, regenerability), disadvantages/limitations (competition, cost, fouling, stability), relative cost (low, medium, high), regeneration potential (easy, difficult, not feasible).

Response 6: Thank you for this valuable suggestion. We agree that the comparative analysis would benefit from a more comprehensive summary table integrating the key performance metrics of zeolites, activated carbons, and their composite materials. In response, we have created a new table-now included as Table 3-which synthesizes the primary mechanisms, target pollutants, advantages, limitations, relative costs, and regeneration potential of each sorbent category.

Additionally, to further clarify economic considerations, we have added Table 4, which expands on cost-related aspects and environmental trade-offs associated with natural zeolites, modified sorbents, and activated carbons.

Location in manuscript:

– Table 3: Page 20, (Track Changes)
– Table 4: Following Section 7, in alignment with techno-economic and environmental assessments.

Comment 7: The synergies must be discussed in dept. The text mentions combined use. Dedicate a paragraph to explaining why the combination is synergistic beyond "separating functions." For instance, zeolites removing NH_4^+ might reduce biofouling on AC, or AC removing organics might prevent pore blockage in zeolites.
Response 7: We appreciate the reviewer's insightful comment. The manuscript has been revised accordingly. A new paragraph was added to provide an in-depth discussion of the synergistic effects between zeolite and activated carbon. This section now explains the complementary adsorption mechanisms, including how zeolites reduce biofouling on activated carbon and how activated carbon prevents pore blockage in zeolites, resulting in enhanced overall purification efficiency and long-term system stability.

Comment 8: The conclusion touches on future research, but it can be more specific. This can be done by addressing gaps and future directions more concisely.
Response 8: We have revised the Conclusion section to clearly highlight specific research gaps and outline concise future directions, as requested.

Location in manuscript: Section Conclusion (all)
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 adsorp-tion 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 ad-sorption, 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 repre-sent a new generation of adaptive "intelligent" materials capable of responding to dy-namic hydroponic conditions.
From a technical and economic point of view, zeolite and carbon-based compo-sites contribute to the introduction of cyclic and sustainable hydroponics methods, re-ducing fertilizer and water consumption, extending the service life of nutrient solu-tions and minimizing waste emissions.

However, existing studies still lack consistent long-term data on field productivity, regeneration efficiency, and environmental im-pacts. 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 ac-tivated carbons, especially when combined with 2D/3D frameworks, provides a syner-gistic effect to create more sustainable, efficient, and circular hydroponic systems. Further development of adaptive, self-healing sorbents will not only increase agricul-tural productivity, but also reduce the negative impact on the environment, paving the way for sustainable food production in conditions of limited resources.

Comment 9: Figure 6 is Unclear: The schematic in Figure 6 is too simplistic and lacks explanatory power. What do "O," "C," "T-TC" represent? This figure should be redesigned to clearly show the synergistic interaction between the zeolite, activated carbon, and the 2D material, perhaps illustrating simultaneous NH_4^+ exchange, organic adsorption, and photocatalytic degradation.

Response 9: Thank you for this helpful comment. We agree that the previous version of Figure 6 did not sufficiently illustrate the mechanistic synergy between zeolites, activated carbon, and 2D materials. In response, we have completely redesigned the figure now presented as Figure 8 due to the addition of new figures to improve clarity and scientific relevance.

Location in manuscript: Page 14, Line 463 (Track Changes), now labelled Figure 8.

Comment 10: Ensure all figures (especially SEM images and graphs) are high-resolution (at least 300 DPI) for publication.

I conclude that this manuscript must be improved prior to publication.

Response 10: Thank you for this important comment. We agree that high-resolution figures are essential for ensuring visual clarity and meeting publication standards. In response, all figures—including SEM images, schematics, and graphs—have been replaced with high-resolution versions (≥300 DPI). We carefully checked each figure to ensure that structural details, labels, and graphical elements are clear and publication-ready.

4. Response to Comments on the Quality of English Language

Point 1:

Thank you for your feedback. We appreciate your confirmation regarding the quality of the English.

5. Additional clarifications