Opinion on Shoaib Mukhtar's Ph.D. thesis entitled „ ***Synthesis and characterization of UV- and visible-light-driven photocatalysts for the degradation of organic pollutants***"

The Ph.D. thesis prepared by Shoaib Mukhtar is a clearly and well-written, demandingly formulated work reflecting a high level of scientific rigor and methodological soundness. The work focuses on the synthesis, characterization, modification and application of a promising "*green*" photocatalyst, g-$C_3N_4$, in light-driven reactions. The research topic is interesting, novel, and possesses scientific significance especially in the light of the global energy crisis which requires developing new strategies to exploit the renewable energy sources. The structure of the thesis is balanced and contains 171 numbered pages. After a short introduction and objective, the literature review section is 34 pages long discussing the relevant background of the research appropriately and shows well-prepared illustrations. The length and the content of the literature review section is sufficient and positions the candidate's own research in the international environment. This section is followed by an experimental part over 16 pages describing all the details of the synthesis, characterization and the application-related experiments. A wide range of analytical techniques had been applied in the research which supports the interpretation of the results in multiple reliable ways. The main findings are presented in the section "*Results and discussion*" covering roughly the half of the thesis in length. In this part, the synthesis of g-$C_3N_4$ from different precursors, the loading with Ag, Bi and Zn-containing species are shown and detailed highlighting the use of these novel photocatalysts in light-driven mineralization processes, the formation of radicals as well as the structural aspects of the materials. The candidate analyses the research results with scientific soundness and reliability and draws the conclusions appropriately using high-quality figures and tables for visualization and comparison. The thesis contains 212 bibliographic references which are formatted correctly.

The thesis points are well-formulated and supported by two publications published in international, peer-reviewed journals, in which the Candidate is the first author. The impact factor of the publications forming the basis of the dissertation is significant, both are classified as Q1. Furthermore, the content of the thesis points reflects the own contribution of the Candidate to the work, hence, I recognize them as new scientific results of Mr. Mukhtar.

I therefore conclude that the work satisfies the formal and content requirements set by the Doctoral School of Chemistry and Environmental Sciences of the University of Pannonia.

During the home-defense of the work I have already served as a reviewer and could monitor the evolution of the thesis in terms of scientific quality and clarity. The Candidate addressed all the emerging questions and concerns with scientific confidence and managed to improve the overall quality of the thesis significantly.

Hereby, I list some questions related to the research and the thesis:

1) It is stated that p-nitrophenol enables the assessment of a photocatalyst's efficiency in real-world pollutants. What are the advantages of pNP over the colored dyes which make it a better model pollutant? Can the degradation mechanism of pNP molecule be used in the explanation of other (real) pollutants' behavior?
2) In case of modification with silver species, can the Candidate imagine charge transfer processes from the AgNPs/clusters towards the g-$C_3N_4$ under UV illumination fulfilling the resonance energy of the AgNP plasmon mode? If yes, which process could be more probable: plasmon-induced charge transport or hot electron injection?
3) Ag-loaded samples can be catalytically active due to the surface silver ion clusters or the formed Ag nanoparticles. It is obvious from the TEM-EDX that light irradiation facilitates the formation of nanoparticles, but what is the form of silver in the beginning

of the reaction? If silver binds to the surface as ion clusters, how stable they can be in aqueous solution during the catalytic reaction itself?

4) What type of other, earth-abundant photocatalyst could show similar electronic structure for utilizing both UV- and visible light excitation? Can p-type $Cu_2O$ or n-type $\alpha$-$Fe_2O_3$ also be considered with or without metal/metal-chalcogenide decoration?
5) What extent can the concentration of the active ingredients (phenols, flavonoids, etc.) be kept constant or controlled in case of extracting them from biological sources? Can the concentration and ratio of these active molecules change from batch-to-batch?
6) Which nanostructure of g-$C_3N_4$ can provide more efficient charge carrier separation and utilization: granular or sheet-like? Melamine as precursor provides rather granular, while urea provides sheet-like carbon nitride. Can the extraction depth of the charge carrier change if the morphology changes?

As a summary of my review, I state that I accept the thesis in its present form and followed by a successful defense, I support the award of the PhD degree to the Candidate.

Budapest, 10th January 2026

Dr. Dániel Zámbó
senior researcher
HUN-REN Centre for Energy Research