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REVIEW

of the doctoral dissertation by Mr Hamza MUMTAZ, MSc Eng.
entitled: "*Experimental analysis of the waste hydrothermal treatment process*"

Thesis supervisor:	Prof. Sebastian Werle, PhD Eng. (Silesian University of Technology)
Assistant supervisor:	Szymon Sobek, PhD (Silesian University of Technology

1. Introduction

The formal basis for the review is the resolution of the Discipline Council for Environmental Engineering, Mining and Power Engineering at the Silesian University of Technology in Gliwice dated 25 September 2025 on the appointment of reviewers for the doctoral dissertation. The review is prepared on the basis of the Act on Higher Education and Science (Journal of Laws of 2024, item 1571, as amended) on the basis of a doctoral dissertation constituting a concise study.

2. Overall assessment of the dissertation

2.1 Scope of the dissertation

The doctoral dissertation submitted for review consists of a series of seven thematically related articles published in scientific journals, which is in accordance with Article 187 section (3) of the Act of 20 July 2018 Law on Higher Education and Science (Journal of Laws 2024, item 1571, as amended), which states that: ***a doctoral dissertation may be*** *a written work, including a scientific monograph,* ***a collection of published and thematically related scientific articles,*** *a design, construction, technological, implementation or artistic work, as well as an independent and separate part of a collective work".*

In the present case, the publications in question, which are described in more detail in chapters 1-7 of the thesis, are devoted to the issue of oxidative liquefaction of selected waste polymer and composite materials, as well as the properties and applications of solid and liquid products of this process. The title of the doctoral thesis corresponds to the subject matter of the publication, and its entirety concerns issues falling within the discipline of environmental engineering, mining and power engineering.

The presented dissertation can be divided into three main parts. The first part is introductory in nature. It consists of summaries in Polish and English and two unnumbered chapters: a chapter describing the structure of the dissertation itself (*Structure of the dissertation)* and a chapter detailing the Doctoral Student's substantive contribution to each of the publications. The second part consisting of numbered chapters 1-8 and unnumbered chapters: *Summary and conclusions* and *Bibliography*, comprises 80 pages and constitutes an 80-page long "Abstract" — the core of the thesis, in which the candidate describes their entire research process in chronological order, divided into subsequent publications. In this part (Chapter 1 — *General Introduction),* the Doctoral Student specifies the research gaps which he identified during the analysis of the state of knowledge and indicates the main goal and sub-goals of the work. The materials and research methods selected for the study are described in Chapter 2 — *Materials and Methods.* Chapters 2-8 cover the results obtained during the Doctoral Student's work (divided into individual publications constituting successive parts of the series) — successive chapters correspond to successive publications in the series. A summary and interpretation of the results obtained are included in the chapter *Summary of the thesis, general conclusions and prospects for further research.* The work is supplemented by a list of figures, tables, symbols and abbreviations used, as well as a bibliography. The second part of the work consists of printouts of all scientific publications comprising the series in question.

In Chapter 1, entitled *General Introduction*, the author presents the global and European context of the problem of polymer waste management and waste from the renewable energy sector. The author begins with an assessment of the scale of the phenomenon: global waste production is expected to exceed 3.4 billion tonnes per year by 2050, with municipal solid waste (MSW), plastics and composites accounting for a significant share. The dynamic development of the renewable energy sector is also highlighted — the installed capacity of wind turbines has exceeded 900 GW, and that of photovoltaics 1.2 TW, which raises new challenges related to the management of used turbine blades (WTBs) and PV panels. The chapter also discusses EU environmental policy: the Waste Framework Directive (2008/98/EC), the Landfill Directive (1999/31/EC), the European Green Deal and the Circular Economy Action Plan (CEAP 2.0). The author points out that the transition from a linear to a circular economy requires innovative technologies for the recovery of raw materials and energy, especially for difficult-to-process materials such as composites and thermosetting polymers. The rest of the chapter reviews research on thermochemical methods (pyrolysis, gasification, hydrothermal processing) and identifies their limitations — high energy consumption and low product selectivity. On this basis, research gaps concerning the effective recovery of valuable compounds from polymer waste were identified. The objectives and tasks of the dissertation were formulated, which are: to develop and optimise the *oxidative liquefaction* process as an effective chemical recycling method for various types of waste. Four groups of materials were planned to be considered as raw materials: waste wind turbine blades (WTBs), used personal protective equipment (PPE), municipal solid waste (MSW) and waste photovoltaic panels withdrawn from service (PV). The aim is to obtain secondary raw materials and to fit into the framework of the Circular Economy (CE). The scientific objective of the work has been clearly presented. I consider the adopted scope and the resulting research plan to be sufficient from the point of view of the objective of the work.

Chapter 2 *Materials and methods* is methodological in nature and forms the basis for experimental research. The author describes four groups of analysed materials and, for each type of waste, presents the standards related to the relevant markings and tests, as well as the results obtained (including elemental analysis). The rest of the chapter presents the configuration of the research station for oxidative liquefaction — a high-pressure reactor (500 ml capacity) operating in a batch system, in which hydrogen peroxide (H_2O_2) was used as the oxidising agent. The plan of experiments, process variables (temperature, pressure, reaction time, oxidant concentration, waste-to-liquid ratio) and the method of process efficiency assessment are described using the following parameters: TSR (*Total Solid Reduction* - degradation efficiency) and OCC (*Oxygenated Chemical Compounds* - production efficiency). The chapter also presents the application of statistical methods — analysis of variance (ANOVA) and response surface methodology (RSM) — to optimise the process and assess the significance of factors affecting product yield. This chapter thus provides the basis for all subsequent experiments, ensuring the methodological consistency of the entire work and enabling the comparison of results between different types of waste.

In Chapter 3, entitled *Experimental Research on the Oxidative Liquefaction of Wind Turbine Blades (WTBS),* the Doctoral Student describes the results of experimental research on the oxidative liquefaction process of polymer composites, which constitute the material of worn wind turbine blades. The author observes that conventional recycling methods (landfilling, pyrolysis, mechanical shredding) are energy-inefficient and do not ensure the recovery of valuable raw materials. The oxidative liquefaction proposed in the thesis, using an aqueous environment and hydrogen peroxide (H_2O_2) as an oxidant, allows for the degradation of epoxy resins and the preservation of the integrity of glass fibres. The study determined the influence of five key parameters: temperature (250-350°C), pressure (20-40 bar), time (30-90 min), oxidant concentration (15-45%) and waste-to-liquid ratio (5-25%). The results showed almost complete degradation of the resins (95–100%) with simultaneous recovery of fibres with an intact structure. The chapter concludes that the tested process can be a scalable method of recycling composites in wind energy.

The title of the next chapter (No. 4): *Oxidative Liquefaction Process of Wind Turbine Blades - Product Analysis* foreshadows its content. In this chapter, the author deepens the analysis of the products obtained after the liquefaction process. He presents the structural and chemical characteristics of the samples before and after the reaction, using FTIR and GC-FID techniques. During the research, volatile fatty acids (VFAs — mainly acetic and formic acid) as the main liquid products, with concentrations of around 210 g/kg. The most favourable process parameters were found to be 250°C, 35 bar, 45 min, 22.5% H_2O_2 and a waste to liquid ratio of 1:20. A compromise was achieved between degradation efficiency and energy consumption. The resulting material retained good mechanical properties, and the liquid products have potential as further raw materials for chemical synthesis or biofuel components. The author emphasises that oxidative liquefaction can be a sustainable alternative to pyrolysis and combustion.

In Chapter 5 of the dissertation, entitled *Comparative Study - Oxidative Liquefaction of Wind Turbine Blades and PPE waste,* the Doctoral Student's research focused on two types of waste: wind turbine blades (WTBs) and used personal protective equipment (PPE), which saw a sharp increase in their share of the waste stream during the COVID-19 pandemic. The aim of the research was to assess the possibility of using a single technology for both polymer streams. It was shown that PPE (consisting mainly of PP and PE plastics) degrades faster and at lower temperatures (200-250°C), achieving a degradation efficiency of 85-90%, with lower energy consumption. WTBs waste requires higher temperatures (~350°C), longer reaction times and has a higher ash content (approx. 58%). The conclusion is that it is necessary to optimise the parameters individually for different types of waste. PPE was found to be a more promising material for chemical recycling, while WTBs were considered a feedstock requiring further process refinement.

Another type of waste (MSW) is discussed in Chapter 6: *Overview of municipal solid waste (MSW) generation — globally and in Poland,* which provides an overview and introduction to further research on the liquefaction of municipal waste. It presents data characterising the municipal waste sector — globally: over 1.2 billion tonnes per year, forecast of 2 billion tonnes in 2025 and nationally — Poland generates approximately 330 kg of waste per capita, below the EU average (480 kg). Current waste management systems (landfilling, mechanical-biological treatment, incineration, recycling) and their limitations were discussed. Particular attention was paid to the insufficient development of waste-to-energy (WTE) technology and the need to implement chemical recycling, e.g. oxidative liquefaction. It was indicated that MSW contains approximately 10-12% of plastics, which represents raw material and energy potential. The author proposes here the integration of innovative methods with the circular economy system in Poland.

Chapter 7, entitled *Comparison of Oxidative Liquefaction of MSW and PPE Waste*, presents an experimental comparison of processes for two waste streams: MSW (municipal waste) and PPE. FTIR analysis results showed that PPE has a more homogeneous polymer composition, which promotes more efficient conversion. Due to its heterogeneity, MSW municipal waste yields lower outputs and requires optimisation of process parameters and conditions. The influence of temperature, oxidant concentration and waste-to-liquid ratio on the yield of oxygenated organic compounds (OCC) and total solid reduction (TSR) was investigated. The optimal conditions for PPE are 200°C, 30 wt.% H_2O_2, 3 wt.% of waste; for MSW — 200^O C, 45 wt.% H_2O_2, 3 wt.% of waste. The results prove that PPE feedstock will enable a more energy-efficient and scalable chemical recycling process, while the use of MSW will require refinement of separation and fraction selection methods.

Chapter 8, entitled *Reprocessing of End-of-Life Photovoltaic Panels,* is devoted to another type of waste under consideration - end-of-life photovoltaic panels. It discusses the growing problem of photovoltaic (PV) waste, the amount of which is increasing with the spread of PV energy generation. An analysis of the material composition of PV modules (glass, aluminium, silicon, EVA and PET polymers) and potential recycling methods (mechanical, chemical and thermal) are presented. The author points to the possibility of adapting oxidative liquefaction methods to recover polymers and organic compounds from the cover layers of panels. Technological barriers (layer adhesion, metal contamination) and the need to integrate chemical processes with glass and silicon recovery have been identified. The chapter serves as a bridge between research on polymer waste and other components of renewable energy production infrastructure.

In Chapter 9, entitled *Summary of the dissertation, general information and prospects for further research,* the author synthesises the results of research on the oxidative liquefaction of various waste streams (WTBs, PPE, MSW) obtained and described in earlier chapters (and primarily in publications constituting individual parts of the series). It has been shown that the process is energy-efficient, allows for high polymer degradation (up to 100%) and yields valuable products (VFAs, OCCs). Key parameters have been identified: temperature, H2O2 concentration and waste-to-liquid ratio. Oxidative liquefaction was assessed as a universal, low-emission technology for polymer waste treatment, in line with the circular economy. Looking ahead, the author points to the need for research on automation, heat recovery and LCA analysis of industrial-scale processes.

The publications submitted for evaluation as part of the publication series and included in the monograph were published between 2023 and 2025 in foreign scientific journals with a high and very high impact factor (IF). It should be emphasised that the total IF of the journals in which the works included in the above series were published is nearly 50, which justifies the conclusion that both the quality of the research and the scientific level of the Doctoral Student are very high. It should be strongly emphasised that the Candidate is the first author in all publications and that his contribution, in accordance with the declarations contained in the publications and the detailed description in the first part of the dissertation, is fundamental. This demonstrates a significant ability to independently plan and perform often complex research experiments, processing of the obtained results and, based on them, preparing valuable scientific publications, which are positively received by the scientific community (the total number of citations of all publications — i.e. not only those constituting the series — amounted to 175 according to the SCOPUS database).

The composition of the entire dissertation, which consists of the chapters discussed above, is clear and concise. The publications presented in the work have been selected in a thoughtful and accurate manner. It should be emphasised that the articles included in the series of publications are very comprehensive, and the diverse research methods and techniques used in them, often very modern, supplemented by an insightful discussion of the research results, confirm the high scientific skills of the Doctoral Student.

Since the articles presented in this series of publications appeared in renowned international scientific journals, I believe that a detailed critical analysis of them is unjustified in this case. Manuscripts submitted for publication in such high-ranking journals are subjected to detailed analysis at the publishing level (by the publisher) and then to an anonymised review process involving several independent reviewers. They usually make a very critical assessment of the submitted material in order to identify errors and shortcomings so that the author has a chance to correct or remove them before the final version is published. It can therefore be assumed that the material constituting the content of individual publications has already been subjected to detailed analysis and substantive verification.

To sum up, I conclude that the series of publications presented has been selected correctly, thanks to which the overall scope of the work described in individual items is consistent and comprehensive.

2.2 Assessment of the appropriateness of the topic selection

The topic of Hamza Mumtaz's doctoral thesis, devoted to the development and analysis of the oxidative liquefaction process of polymer waste from various sectors of the economy (wind turbine blades, PPE waste, MSW and photovoltaic panels), should be considered extremely relevant, timely and important from both a scientific and practical point of view. The issue of plastic and composite waste management, especially from renewable energy sources, is one of the greatest challenges of the modern circular economy (CE). The choice of topic is a response to a real research gap in the field of chemical recycling of thermosetting materials, which until now have been largely landfilled or incinerated. The author has attempted to develop a new, sustainable technology for the chemical processing of this type of waste, using *oxidative liquefaction* — a process that has been little studied to date, but which is promising due to its moderate reaction conditions, low energy consumption and potential for recovering valuable liquid products.

The topic of the dissertation also fits perfectly with the priorities of the European Union's environmental policy, including the European Green Deal, the industrial decarbonisation strategy and the secondary raw materials economy. The dissertation is interdisciplinary in nature, combining knowledge in the fields of chemical engineering, environmental technology, materials science and life cycle assessment (LCA). It covers both the cognitive dimension (understanding the mechanisms of polymer degradation in an oxidative environment) and the application dimension (assessment of the potential for the use of liquefaction products in industry).

In summary, it should be noted that the choice of topic for this thesis is fully justified from a scientific, economic and environmental perspective. The dissertation addresses an issue of great strategic importance, and the author's approach demonstrates an awareness of contemporary challenges in the field of polymer recycling and energy transformation. The correct choice of the subject of the study and its significant perspective, both in terms of research and its practical application, is evidenced by the financial support which the Doctoral Student received under a research programme funded by the National Science Centre as part of the OPUS 2 competition. This is the best confirmation of the importance and significance of the subject matter analysed and developed in the thesis.

2.3 Correctness of the considerations, results and conclusions obtained, and critical comments

The considerations presented in the dissertation are characterised by factual accuracy and logical consistency. The author consistently follows the line of reasoning — from identifying the research problem, through reviewing the literature and justifying the choice of methods, to analysing the results and formulating conclusions. The structure of the thesis is clear, and the methodology used is correct from the point of view of both environmental engineering and chemical and process engineering. The experimental research was carried out in a careful and repeatable manner, in accordance with the principles of measurement and analytical correctness. The results were analysed using appropriate statistical methods, including analysis of variance (ANOVA) and response surface methodology (RSM), which allowed for an objective assessment of the impact of individual process parameters. The interpretations of the data are logical and based on literature knowledge, and the conclusions are synthetic and do not go beyond the results obtained. Another advantage is the multi-threaded comparison of different types of waste (WTBs, PPE, MSW, PV), which allows us to capture the differences in their reactivity and liquefaction efficiency.

Particular recognition should be given to the comprehensive approach to the oxidative liquefaction process, which takes into account both the analysis of product properties (FTIR, GCFID, SEM-EDS) and the assessment of the technology's implementation potential. The conclusions are well justified experimentally, and the quantitative relationships between process parameters and product yields presented in the dissertation testify to the reliability of the data analysis.

The content of the dissertation proves that the Doctoral Student is very well versed in the subject matter. I have no substantive comments on the content of the dissertation, I find no shortcomings in this respect, and I assess the Doctoral Student's knowledge of the subject matter — including his professional and scientific preparation — very positively.

However, the issues listed below provide food for thought for further scientific discussion, and I would ask for comments on them during the defence of the thesis:

1) In Chapter 1, the Doctoral Student lists the technologies currently used for the management of composite waste materials and indicates that chemical recycling is likely to be the most promising direction for recovering valuable products from them. The question is: are there currently any alternatives to the mentioned recycling technologies (not only chemical) for such materials, and what levels of technological readiness can be attributed to them? Information on commercially

available chemical recycling technologies and their comparison with the proposed oxidative liquefaction method would help to highlight the innovative nature of the proposed solution.

2) Can each of the specified types of waste (WTB, PV, PPE, MSW) be assigned a separate waste code and are they subject to selective collection (question specifically in the context of PPE) or not — and if so, should additional installations for sorting/separating PPE waste, e.g. from the general MSW stream, be planned as part of the target chemical recycling installation? Apart from healthcare sector entities, is there an organisational or formal legal possibility of selective collection of such material to ensure its supply to the planned recycling facility in quantities sufficient to make its operation economically viable?

3) On p. 27, the Candidate writes*, "The presence of trace elements, including copper and rare earth elements such as cerium, praseodymium, and neodymium, suggests a potential* ***resource*** *value" and* then argues that *"the relatively low concentrations of these elements underscore the economic challenges associated with their recovery from waste materials".* What was the basis for this thesis and whether (and to what extent) the proposed oxidative liquefaction process could enable (or prevent) further recovery of rare earth trace metals? Such recovery of additional valuable raw materials would certainly have an impact on the economics of the process and the possibility of wider implementation of the technology.

4) What determined the choice of MSW (municipal solid waste) for the analyses, and would it not be more advantageous to use RDF (SRF) material as a raw material, whose properties (including morphology) are much more uniform than those of MSW? As a result, could the number of unit processes involved in the preparation of the raw material (e.g. Cl reduction process) prior to the actual oxidative liquefaction reactions be reduced?

5) Can the results obtained be used to estimate the net energy consumed during the oxidative liquefaction process (heat, electricity, compression work, cooling) in relation to the quantity and energy value of the products obtained? This information is valuable in determining if, after scaling up, the process has a chance of being energy self-sufficient or whether it will require external power supply (which will translate into operating costs). In turn, benchmarking against existing chemical recycling technologies: pyrolysis, hydrothermal decomposition or gasification, can help determine whether the proposed process has competitive advantages in terms of cost, efficiency or the environment — this is important from the perspective of a future investor (the Candidate - rightly so - mentions further development and commercialisation of this technology).

6) Can the results obtained be used to predict the efficiency and composition of similar processes for continuous flow reactors?

7) Which industries may be interested in the chemical recycling products produced (solid and liquid products — what may be the market absorption and main customers?).

3. Final conclusions

The dissertation by Hamza Mumtaz, MSc, illustrates a comprehensive approach to scientific research on the oxidative liquefaction of polymer waste — an innovative chemical recycling method that enables the recovery of raw materials from difficult-to-process materials. The research covered four representative waste streams: wind turbine blades (WTB), personal protective equipment (PPE), municipal solid waste (MSW) and end-of-life photovoltaic panels (PV). The Author proved that the oxidative liquefaction process, carried out under moderate conditions of 200– 350°C 20–40 bar) using hydrogen peroxide as an oxidising agent, allows for the effective decomposition of polymer matrices and their conversion into valuable liquid products — mainly oxygen-containing organic compounds (OCCs) such as acetic, formic and propionic acids and alcohols. The use of statistical methods (ANOVA, RSM) enabled the optimisation of the process and the determination of key parameters determining its efficiency.

The tests yielded high solid weight reduction rates (TSR/TPD) – above 95% for PPE and MSW – and significant liquid product yields (up to 213 g/kg for PPE). For wind turbine blades, the process enabled almost complete degradation of epoxy resins while preserving glass fibres, whereas for PV, efficiency was limited by mineral composition and the presence of metals. The author also demonstrated the exothermic nature of the reaction, which confirms the potential energy efficiency of the process when properly integrated technologically.

The developed method was assessed as universal and flexible, applicable to various types of waste containing thermoplastic and thermosetting polymers. The obtained products have chemical and energy value and can be used as biofuel components or raw materials for organic synthesis.

In the application layer, the author emphasised the importance of further developing the technology towards continuous (flow) processes, integration with heat recovery and the use of catalysts, which would increase the efficiency and scalability of the solution. Attention was also drawn to the need to analyse environmental and economic aspects, especially when processing waste containing halogens and heavy metals.

In summary, the research showed that oxidative liquefaction is a promising, low-emission chemical recycling method that could become an important element of the circular economy. The dissertation makes a significant contribution to the development of knowledge about the thermochemical conversion of polymer waste and provides a solid basis for further research and implementation work in the field of sustainable waste treatment technologies.

The scope of the work performed constitutes the original achievement of the Doctoral Student, and the results obtained during the work, in addition to highlighting important scientific elements, provide useful conclusions, which are therefore valuable from a practical point of view.

The interdisciplinary nature of the work, combining elements of environmental engineering, chemical engineering and materials engineering, as well as its practical dimension, deserve special recognition. The results obtained in the research may form the basis for further implementation and development work in the field of innovative recycling technologies.

The work is carefully edited, linguistically correct and logically structured. The comments mentioned above are supplementary in nature and do not affect the overall, very positive assessment of the work.

To sum up the above, I conclude as follows:

1) Based on the doctoral dissertation submitted to me for review, and taking into account the comments and observations presented above, I conclude that the dissertation entitled *"Experimental analysis of the waste hydrothermal treatment process"* presented by Mr Hamza Mumtaz, MSc, fully meets the conditions and requirements for doctoral dissertations specified in Article 13. I and referred to in point 1 of the Act.

2) The doctoral dissertation presents an original solution to a scientific problem and demonstrates the Doctoral Student's general theoretical knowledge in the scientific discipline of environmental engineering, mining and energy. It also proves his ability to conduct independent

scientific work, including the planning and implementation of a very wide range of experimental research, discussion and interpretation of the results obtained.

3) The work has valuable practical aspects, and the results achieved may be useful and further developed for application in the fields of environmental engineering, chemical engineering and waste management.

In view of the above facts, I hereby request the High Discipline Council for Environmental Engineering, Mining and Power Engineering at the Silesian University of Technology in Gliwice to admit Mr. Mumtaz, MSc, Eng., to the next stages of the doctoral degree procedure.

[signature of the Reviewer]