AGH UNIVERSITY OF KRAKOW
STANISŁAW STASZIC MINING AND METALLURGICAL ACADEMY IN KRAKOW
Faculty of Metals Engineering and Industrial Computer Science
Department of Heat Engineering and Environmental Protection
Prof. Aneta Magdziarz, PhD

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REVIEW OF THE DOCTORAL DISSERTATION
by Mr Hamza Mumtaz, MSc, Eng.
entitled: *"Experimental analysis* of *the waste hydrothermal treatment process"*
supervised by Prof. Sebastian Werle, PhD, Eng. and Szymon Sobek, PhD, Eng.
at the Faculty of Energy and Environmental Engineering at
the Silesian University of Technology in Gliwice

1. Basis for the preparation of the review

This review of the doctoral dissertation of Mr Hamza Mumtaz, MSc, Eng., was prepared under the agreement dated 8 October 2025 with the Silesian University of Technology, represented by Prof. Mariusz Dudziak, PhD, Eng., based on Resolution No. 218/2025 of the Discipline Council for Environmental Engineering, Mining and Power Engineering of the Silesian University of Technology dated 25 September 2025 on the appointment of reviewers.

2. Introduction

Dynamic economic development, which comprises renewable energy sources and a rapid increase in demand for advanced polymer materials, faces the challenge of a growing amount of waste from modern technologies and everyday products. The energy transition based on renewable energy sources, which is important for reducing greenhouse gas emissions, is unfortunately a source of new types of waste that require the development of innovative and sustainable recycling methods with the possibility of recovery of raw materials. Such measures are particularly important in the context of the circular economy (CE).

Those types of waste include, among others, used wind turbine blades and waste from photovoltaic panels. It is estimated that in the coming years, hundreds of thousands of tonnes of wind turbine blades will be decommissioned due to the ageing of composite materials and technological advances in their design. The blades contain glass fibres, epoxy resins and other polymers, which makes them difficult to dispose of with the use of traditional mechanical or thermal methods. Their storage is costly and burdensome for the environment, while incineration can lead to the emission of toxic substances. For this reason, research is being conducted on chemical processes such as *oxidative liquefaction* and solvolysis, which enable the decomposition of the polymer structure and the recovery of valuable organic compounds. At the same time, research into innovative technologies for recovering raw materials from PV panels (which are a source of glass, aluminium, silicon and polymer resins, among other things), including thermal-chemical methods, is a key element of sustainable waste management.

Waste from the healthcare sector, especially personal protective equipment (PPE) such as masks, gowns and gloves, has also become a significant challenge. The COVID-19 pandemic highlighted the scale of this problem, causing a sharp increase in the amount of single-use polymer waste. That type of waste can be processed to produce high value-added products such as oxygen compounds and synthetic fuels. The growing amount of municipal waste, which is very diverse in composition and therefore difficult to process, is becoming an increasing environmental challenge. Municipal waste contains significant amounts of plastics, textiles and multi-material waste, which makes it difficult

to be recycled effectively. New technologies are also being developed in this area, with the aim of simultaneously reduction of waste volume and converting it into valuable chemical or energy resources, thereby reducing emissions, recovering raw materials and minimising the negative impact on the environment.

All of the above-mentioned types of waste have a polymer structure, which means that their processing by mechanical and thermal methods encounters numerous limitations and problems, but on the other hand, they can be a valuable source of raw materials for the chemical and materials industries.

The use of processes based on oxidation, hydrothermal and solvolysis opens up new possibilities for the processing of the above-mentioned waste. From the perspective of the circular economy, research into these processes is not only of technological importance, but also of strategic and environmental significance. This is because it enables the recovery of resources, the production of valuable chemicals and a reduction in the amount of waste sent to landfill, while at the same time reducing the carbon footprint of the entire process. Thus, it forms the basis for further research on integrated waste treatment systems that combine technological, economic and environmental aspects.

In view of the above, it should be emphasised that Mr Hamza Mumtaz's doctoral thesis addresses an extremely topical and important research topic concerning modern methods of processing polymer waste from various sectors of the economy, such as wind energy, photovoltaics, the medical sector and municipal services. In the face of global environmental challenges, the growing problem of composite waste management and the need to use renewable energy sources, the presented research results constitute a significant contribution to the development of the circular economy and sustainable recycling technologies. The doctoral candidate comprehensively analysed the possibilities of recovering raw materials from waste with a complex polymer structure through the use of innovative chemical processes, in particular oxidative liquefaction, hydrothermal processing and solvolysis. In his research, he used advanced analytical techniques, including Fourier transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM) and thermogravimetric analysis, (TGA), gas chromatography with flame ionisation detection (GC-FID), performed kinetic and thermodynamic analysis of the processes, and conducted an environmental analysis using the LCA method, which demonstrates a broad, interdisciplinary approach to the problem.

I conclude that the research topic is of high scientific and practical value, and the scope of the analyses is fully justified and in line with current global trends in the field of composite and polymer recycling. In my opinion, the doctoral dissertation by Hamza Mumtaz, MSc, entitled *"Experimental analysis of the waste hydrothermal treatment process"* is an example of a modern, well-thought-out and practically oriented approach to the problem of waste management, combining advanced knowledge in the fields of chemistry, process engineering and environmental protection. The research results provide valuable data to support the development of raw material recovery technologies and the implementation of circular economy principles, which is of significant importance for waste management in the renewable energy and health protection sectors.

3. Assessment of the thesis topic and its scope

The doctoral dissertation of Hamza Mumtaz, MSc, was carried out as part of the NCN (OPUS-21) research project entitled "Oxidative liquefaction of waste plastics. Experimental research with multidimensional data analysis using chemometric methods" and was additionally developed as part of the *European University on Responsible Consumption and Production* consortium*, EURECA-PRO*.

The reviewed doctoral dissertation was prepared in the form of an article-based thesis. It comprises seven scientific publications, published in renowned JCR-listed journals with high impact factors, concerning the application of oxidative liquefaction and hydrothermal waste treatment processes. The thesis consists of two main parts. The first part is a comprehensive presentation of the discussed issue and the most important research results (102 pages with a list of 132 references), while the second part consists of printouts of scientific articles comprising the series in question.

In the introductory part (before the main chapters), the doctoral candidate included *a Summary* in which he concisely presented the researched issue, taking into account the importance of the oxidative liquefaction process as an innovative method of chemical recycling of polymer and municipal waste, allowing for the recovery of valuable chemical compounds. He then clearly presented the structure of the doctoral dissertation, with particular emphasis on his publications. For the publications included in the series, the doctoral candidate provided information on the substantive scope of his contribution to their preparation. Hamza Mumtaz, MSc, is the first and corresponding author in all seven publications, which clearly confirms his leading role in the planning, implementation and interpretation of the research results and testifies to the doctoral candidate's scientific independence.

It should be emphasised that the publications included in the dissertation were published in renowned international scientific journals, i.e. *Sustainable Chemistry and Pharmacy, Renewable Energy*, *Energy*, *Journal of Environmental Management* and *Clean Technologies and Environmental Policy,* and their subject matter constitutes a coherent, consistently developed research cycle.

Chapter 1*, General Information,* was developed on the basis of Article 1 (Appendix A). The chapter is an introduction to the research topic and provides the theoretical background for the rest of the dissertation. The author presents the context of the problem, the rationale for undertaking the research and its significance in the perspective of the circular economy and environmental protection in a thoughtful and logical manner. The doctoral candidate describes the problem of polymer and composite waste generation, paying particular attention to waste generated in the following industries: wind energy (turbine blades), photovoltaics, medicine (personal protective equipment, PPE) and municipal services. The author cites current literature data on the amount of this waste and points to the difficulties in managing it using traditional methods, such as mechanical recycling or incineration. He then describes the available waste treatment methods, such as pyrolysis, gasification, solvolysis and hydrothermal treatment processes. The conclusion of this chapter is the doctoral candidate's identification of research gaps, followed by the statement of the aim of the thesis. The author accurately points out that there are research gaps in the area of existing work on hydrothermal and oxidative waste treatment. He points to the lack of detailed analysis of process parameters and their optimisation, the limited application of technology for complex types of waste, insufficient comparison of process efficiency depending on material composition, and the lack of industrial implementation resulting from technical and economic barriers. This means that the research topic is fully justified, as it addresses real gaps in existing research and needs in the field of effective processing of complex waste. Finally, the doctoral candidate presents the main objective of the work, which was to study the oxidative liquefaction process as an advanced method of waste management, such as wind turbine blades, personal protective equipment, photovoltaic panels and municipal waste, through the degradation of their organic matrix in an oxidising environment, leading to the formation of secondary compounds (e.g. oxygen [cleaning] compounds, OCCs). The specific objectives were: physicochemical characterisation of selected waste types, identification of key parameters affecting the efficiency of the process (temperature, pressure, reagent ratio, oxidant concentration), determination of the reaction mechanism and kinetics of polymer degradation, chemical analysis of the liquid products obtained, and statistical analysis of the results obtained.

In Chapter 2, entitled *Materials and Methods*, the author presented a description of the materials used in the research, i.e.: *wind turbine blades* (WTB), *personal protective equipment* (*PPE*), waste from *photovoltaic panels (*PV*)* and municipal solid waste (*MSW)*, and provided their physicochemical characteristics. The next part of the chapter describes the experimental setup used in the oxidative liquefaction of waste. The author presents a diagram of the reactor in which the research was carried out, including the method of reagent dosing, reaction time, waste-to-liquid ratio, and types of oxidants used. Next, the plan and structure of the experiment were presented, developed using statistical methods describing the relationships between reaction parameters and process efficiency, as well as the identification of significant factors affecting the yield of oxygen compounds (OCCs).

In Chapter 3, based on the article *"An experimental investigation and process optimisation of the oxidative liquefaction process as the recycling method of end-of-life wind turbine blades" (Renewable Energy*, 2023, Appendix B), the doctoral candidate presents the results of research on the use of oxidative liquefaction of used wind turbine blades. The author presented the impact of key process parameters on the efficiency and composition of reaction products, confirming the effectiveness of this technology in the decomposition of composite materials and the recovery of valuable oxygen compounds. The results obtained, supported by statistical analysis, prove that the process can be an effective and sustainable method of managing polymer-composite waste.

Chapter 4 is a continuation and extension of the research results presented in the previous chapter on the use of the oxidative liquefaction process as an alternative method of recycling used wind turbine blades. This chapter is based on the publication *"Oxidative liquefaction as an alternative method of recycling and the pyrolysis kinetics of wind turbine blades"* (Energy, 2023, Appendix C). In this work, the author extended the analysis to include kinetic and thermal studies of composite materials. The use of TGA methods and statistical analysis demonstrates the high level of sophistication of the research and the ability to combine experimental and computational studies.

The results of research on the oxidative liquefaction of polymer waste from the medical sector (PPE) are presented in an article published in *the Journal* of *Environmental Management* (Appendix D). Particularly noteworthy is the use of the following methods: *Central Composite Face-Centered Design (*CCF) and *Central Composition Design with Fractional Factorial Design,* which enable a precise assessment of the impact of parameters such as temperature (250-350°C), pressure (20-40 bar), residence time (30-90 min), H_2O_2 concentration (15-45%) and waste-liquid ratio (5-25%) on the efficiency of the process. Statistical analysis (ANOVA) allowed for the conditions ensuring maximum waste reduction and the highest yield of liquid products to be determined.

In an article published in *Clean Technologies and Environmental Policy* (Appendix E), the author focuses on analysing the potential of *Waste Wet Oxidation* technology as an alternative method of recovering raw materials and producing chemical compounds from municipal waste. The study is of a review and analytical nature and shows that *Waste Wet Oxidation* technology is a viable alternative to traditional waste disposal methods and can contribute to the development of a circular economy in Poland.

A comparison of studies on the oxidative liquefaction of municipal solid waste (MSW) and personal protective equipment (PPE) is presented in an article published in *Renewable Energy* (Appendix F). The study shows that the higher carbon and volatile content in PPE samples indicates a greater potential for this waste to be converted into secondary compounds. On the other hand, the high content of inorganic fractions in municipal solid waste (MSW) may limit the efficiency of the process. It has been confirmed that lower temperatures and lower oxidant concentrations for PPE, moderate concentrations for MSW, and a low waste-to-liquid ratio ensure an efficient process with minimum energy consumption and maximum recovery of raw materials.

Research on the recycling of end-of-life photovoltaic (PV) panels is presented in the article entitled *"Innovative recycling of end-of-life photovoltaic panels with the aim* of *polymer degradation and valuable chemical production",* published in the journal *Renewable Energy* (Appendix F). This publication is the culmination of the experimental part of the dissertation and presents the results of research on the processing of end-of-life PV, which indicate that the processing of end-of-life photovoltaic (PV) panels is a significant challenge, mainly due to their complex material composition and multi-layer structure. However, the use of an oxidative liquefaction process allows for a reduction in waste and the recovery of valuable chemical compounds.

4. Evaluation of the dissertation

I give a positive assessment to the doctoral dissertation by Hamza Mumtaz, MSc,Eng. entitled *"Experimental analysis of the waste hydrothermal treatment process"*. It constitutes a significant contribution to the development of scientific knowledge in the field of modern methods of processing various waste streams, including wind turbine blades, personal protective equipment, photovoltaic panels and municipal waste. Conducting research on such a broad scale required extensive interdisciplinary knowledge, covering issues in environmental engineering, chemical engineering, materials engineering and environmental protection. The work is experimental in nature and required the ability to conduct complex experiments in high-pressure reactors, precisely develop experimental plans and interpret the results obtained using advanced analytical techniques such as TGA, FTIR, GC-FID, GC-MS and SEM-EDS. The doctoral candidate has demonstrated high research competence and the ability to independently conduct and interpret research results. The research solutions developed by the doctoral candidate have contributed to the advancement of knowledge in the field of oxidative liquefaction process optimisation and indicate real possibilities for their implementation in industrial practice.

I consider the following to be the doctoral candidate's main achievements:

- The application of the oxidative liquefaction method to the processing of difficult waste streams (wind turbine blades, personal protective equipment, photovoltaic panels, municipal waste).
- The use of statistical methods for process design and optimisation (he developed a matrix for analysing the impact of temperature, pressure, oxidant concentration, reaction time and waste-liquid ratio on process efficiency).
- Application of advanced analytical techniques to characterise raw materials and process products (used TGA, FTIR, GC-FID, GC-MS, SEM), identified the main groups of organic compounds formed in the oxidative liquefaction process.
- A proof of the potential of the oxidative liquefaction process in reducing waste and pollutant emissions.
- A proof of the ability to conduct interdisciplinary research.

During the analysis of the doctoral dissertation, I had several observations and questions that may serve as a starting point for further scientific discussion with the author. Here are the most important ones:

a) In subsection 1.2.2, the doctoral candidate describes waste treatment methods. He mentions the decomposition of biomass fibres, i.e. cellulose, hemicellulose and lignin. Can an analogy to lignocellulosic biomass be found in the waste materials studied by the doctoral candidate?
b) On page 29, in Table 2.2, the doctoral candidate presents a technical analysis and chemical composition of the waste studied. Particular attention is drawn to the high ash content in WTB and PV. Did the doctoral candidate study the chemical composition of the ash? What is

the impact of the chemical composition of ash on the oxidative liquefaction process? Can certain metals contained in the mineral phase of the waste have a catalytic effect?

c) Can a catalyst be used in the oxidative liquefaction process, especially in the case of materials with limited susceptibility to decomposition?
d) Selection of oxidative liquefaction process parameters (e.g. Table 2.3): based on the research results obtained, can the doctoral candidate define which parameter has the greatest impact on the yield of valuable organic compounds, e.g. esters, carboxylic acids?
e) What about the solid residue after the oxidative liquefaction process? How much solid residue remains after the process? Did the doctoral candidate analyse the chemical composition of the solid phase? Is it possible to use this fraction?
f) Please systematise which products (organic compounds) can be obtained from the waste materials studied by the doctoral candidate.
g) Is it possible to combine oxidative liquefaction with other industrial-scale waste conversion methods?

I would like to emphasise that the above comments are debatable, do not diminish the scientific value of the reviewed work, and I hope that they will be a starting point for discussion during its public defence and will motivate the doctoral candidate's future research.

5. Summary

The doctoral dissertation submitted for review by Hamza Mumtaz, MSc,Eng. entitled "*Experimental Analysis* of *the Waste Hydrothermal Treatment Process*" responds to the scientific challenge of developing effective and sustainable methods for processing polymer and composite waste. The subject matter of the thesis fits perfectly into the current research trends related to the circular economy, emission reduction and the recovery of raw materials from difficult-to-process waste. The doctoral candidate demonstrated scientific maturity and a high level of research competence by formulating the objectives of the work and consistently implementing a complex plan of experimental research. The dissertation applies an innovative research approach based on the processes of oxidative liquefaction and wet oxidation, which are alternatives to classical methods of thermochemical waste treatment.

Hamza Mumtaz, MSc, Eng. has demonstrated a thorough theoretical knowledge of environmental engineering, chemical engineering and chemical environmental protection, as well as practical skills in conducting advanced experiments and interpreting results. The use of modern analytical methods (TGA, FTIR, GC-MS, SEM-EDS) and the precise processing of results confirm his research competence and scientific independence.

It is also worth noting the doctoral candidate's impressive publication record, which includes several articles published in renowned scientific journals with a high impact factor *(Renewable Energy*, *Energy*, *Journal* of *Environmental Management*, *Journal* of *Cleaner Production, Energies*). These publications form an integral part of the dissertation and constitute a logical, coherent scientific whole.

In summary, the doctoral dissertation by Hamza Mumtaz, MSc, is an original, valuable and innovative scientific study that makes a significant contribution to the development of sustainable waste treatment technology and the circular economy.

I am convinced that the reviewed doctoral dissertation by Mr Hamza Mumtaz*,* MSc*,* Eng. entitled *"Experimental analysis* of *the waste hydrothermal treatment process"* meets the conditions and requirements for doctoral dissertations specified in Article 187 of the Act of 20 July 2018 - Law on Higher Education and Science. **In view of the above, I submit a motion to the Discipline Council for**

Environmental Engineering, Mining and Power Engineering at the Silesian University of Technology to admit the doctoral candidate to the next stages of the doctoral procedure.

Additionally, **I request that the dissertation be recognised as an outstanding one**. I justify my request as follows:

- the thesis addresses key challenges of the modern economy and energy sector in the management of waste from modern technologies (wind turbine blades, photovoltaic panels, personal protective equipment, municipal waste);
- the doctoral candidate has developed and refined the oxidative liquefaction method as an alternative to classic thermal recycling processes;
- the scope of the research is very comprehensive, and the results obtained are very extensive and substantively diverse;
- the scientific publications included in the series have been published in renowned scientific journals with a high impact factor;
- the doctoral candidate's bibliometric indicators are at a very high level, according to the Web of Science database: the total number of publications is 13, the number of citations is 130, and the Hirsch index is 6, which is worth emphasising and testifies to the recognition of the research conducted by the scientific community.

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