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Review Report on Doctoral Thesis, PhD candidate: mgr Marcellus Arnold

Thesis title: „Innovative impregnation techniques and process optimization for shaping the physicochemical, functional, enzymatic, and sensory properties of freeze-dried apple snacks”.

Supervisor: prof. dr hab. Anna Gramza-Michałowska, Poznań University of Life Sciences, Department of Gastronomy Science and Functional Foods, Faculty of Food Science and Nutrition.

Legal basis: Act of 20 July 2018 - Law on Higher Education and Science (Journal of Laws of 2023, item 742, as amended)

Justification for undertaking the research topic and formal evaluation of the work

The justification for undertaking the research topic is well grounded in current public health challenges, particularly the high prevalence of osteoporosis and calcium deficiency. The study addresses the growing demand for functional foods derived from local resources, aligning with the objectives of the United Nations' Sustainable Development Goals. By focusing on the enrichment of freeze-dried apples with bioactive compounds from sea buckthorn juice and calcium, the research responds to both nutritional and technological needs. Moreover, the inclusion of quality-related aspects, such as enzymatic browning, storage stability, and sensory properties, further supports the relevance and practical applicability of the selected research topic.

The dissertation has been prepared in accordance with the principles established for doctoral theses (Article 187, paragraph 3 of the Law). In line with Article 187, paragraph 4 of the Law, the work includes abstracts in both English and Polish, which concisely outline the research background, objectives, main findings, and conclusions of the study.

The doctoral dissertation by MSc Marcellus Arnold, titled "Innovative Impregnation Techniques and Process Optimization for Shaping the Physicochemical, Functional, Enzymatic, and Sensory Properties of Freeze-Dried Apple Snacks", is based on a collection of five papers published between 2022 and 2025 in well-regarded journals covering aspects of food technology, functional foods, and nutrition:

A1 Arnold, M., & Gramza-Michalowska, A. (2024). Recent development on the chemical composition and phenolic extraction methods of apple (*Malus domestica*)—a review. *Food and Bioprocess Technology*, 17(9), 2519-2560.

A2 Arnold, M., & Gramza-Michałowska, A. (2022). Enzymatic browning in apple products and its



inhibition treatments: a comprehensive review. *Comprehensive Reviews in Food Science and Food Safety*, 21(6), 5038-5076.

A3 Arnold, M., Białas, W., Kulczyński, B., Multisona, R. R., Suliburska, J., Świeca, M., Wojdyło, A., & Gramza-Michałowska, A. (2025). Product development study of freeze-dried apples enriched with sea buckthorn juice and calcium lactate. *Molecules*, 30(7), 1504.

A4 Arnold, M., Tylewicz, U., Suliburska, J., Świeca, M., Wojdyło, A., & Gramza-Michałowska, A. (2025). Vacuum and ultrasound-assisted impregnation of Gala apple with sea buckthorn juice and calcium lactate: functional properties, antioxidant profile, and activity of polyphenol oxidase and peroxidase of freeze-dried products. *Polish Journal of Food and Nutrition Sciences*, 75(3), 283-302.

A5 Arnold, M., Suliburska, J., Świeca, M., Wojdyło, A., & Gramza-Michałowska, A. (2025). Storage stability of bioactive-enriched freeze-dried Gala apples: functional properties, sensory evaluation, and enzymatic browning. *Food and Bioprocess Technology*.

Collectively, the five publications have a total impact factor (IF) of 33.3 and a total MNiSW score of 640 points, reflecting the scientific visibility and recognized value of the candidate's contributions in the field of food technology, functional foods, and nutrition.

All publications are multi-author papers in which the PhD candidate is listed as the first author. According to the attached declarations, the candidate's contribution included the development of the research concept, planning and conducting the experiments, selection and application of research methods, analysis and interpretation of results, and preparation of both the initial and final versions of the manuscripts.

The research was financially supported by several grants, including the Preludium program of the National Science Centre, Poland (2023/49/N/NZ9/00862), funding from the Polish Ministry of Education and Science (SKN/SP/534738/2022), the Regional Initiative Excellence program (005/RID/2018/19), and the Young Scientist Research Grant from the Faculty of Food Science and Nutrition, Poznań University of Life Sciences (2022-2023), as well as statutory funds of the Department of Gastronomy Sciences and Functional Foods. This support underlines the institutional recognition and relevance of the conducted research.

The dissertation includes abstracts in both English and Polish, which concisely present the research background, objectives, main findings, and conclusions, providing the reader with a clear overview of the study. The preliminary sections also feature a list of abbreviations, which, together with the abstracts, facilitate reading and understanding of the dissertation by offering quick reference to technical terms and shorthand used throughout the work.

The main body of the dissertation begins with Chapter 1 (Introduction) provides the theoretical background for the research. It addresses osteoporosis and calcium deficiency as relevant public health challenges, introduces the concept of functional foods based on local resources with particular emphasis on impregnation techniques, and discusses methods for preventing enzymatic browning in apple products. The



chapter concludes with a synthesis of the reviewed literature, leading logically to the formulation of the research objectives.

Chapter 2 presents the aims and hypotheses of the study. The main aim and specific objectives are clearly defined and directly derived from the identified research problem. The formulated hypotheses are coherent and testable. The chapter also includes a research scheme that outlines the experimental design and relationships between objectives, hypotheses, and methodological approaches.

Chapter 3 (Materials and Methods) describes the materials and experimental procedures applied in the study. The methods related to apple preparation, impregnation, freeze-drying, and the analysis of physicochemical, functional, enzymatic, and sensory properties are appropriately selected and sufficiently detailed to ensure reproducibility. The structure of the chapter is consistent with the research objectives.

Chapter 4 (Research Findings) presents the experimental results in a three-stage structure consistent with the research scheme and the publications constituting the dissertation. The chapter covers the optimization of atmospheric-pressure impregnation, the application of vacuum and ultrasound-assisted impregnation techniques, and the evaluation of the three-month storage stability of enriched freeze-dried apple products. This structure ensures coherence between the research objectives, hypotheses, and the obtained results.

Chapter 5 (Conclusions and Practical Implications) closes the dissertation by summarizing the main findings and outlining their practical relevance. The conclusions are directly linked to the research objectives and hypotheses, maintaining the logical coherence of the work. The dissertation also includes a complete list of references and a section specifying the publications forming its basis, with attached declarations confirming the candidate's substantial and independent contribution. Along with abstracts, lists of abbreviations, and the clear chapter structure, these elements ensure the dissertation is well-organized, transparent, and accessible to the reader.

Academic evaluation of the dissertation

Since the research findings have already undergone peer review during the publication process, this section focuses primarily on their significance for the advancement of knowledge, with only limited reference to specific numerical data.

The set of publications forming the dissertation constitutes a coherent and logically structured research cycle. The first review paper, "Recent development on the chemical composition and phenolic extraction methods of apple (*Malus domestica*) – a review" (A1), provides a comprehensive and up-to-date overview of the nutritional and bioactive composition of apples, with particular emphasis on phenolic compounds as key contributors to their health-promoting properties. This review systematically analyzes the variability of apple composition across cultivars and growing regions and critically evaluates conventional and modern phenolic extraction methods applied to different apple matrices (flesh, peel, pomace, pulp). Importantly, the paper also addresses aspects of sustainability through the discussion of food-grade and green solvents, thereby linking nutritional quality with environmental considerations. By



thoroughly synthesizing existing knowledge on apple bioactive compounds and extraction strategies, publication A1 establishes a solid scientific foundation for the subsequent experimental studies. It clearly justifies the selection of apples as a functional food matrix and supports the technological approaches applied later in the dissertation, including impregnation and enrichment processes. In this context, the review does not constitute an isolated contribution but rather serves as an essential conceptual and methodological starting point for the original research presented in the following publications.

The second review paper, “Enzymatic browning in apple products and its inhibition treatments: a comprehensive review” (A2), logically complements the first review by addressing a key technological challenge associated with apple processing, namely enzymatic browning. The paper provides a thorough synthesis of recent studies on the mechanisms of enzymatic browning in minimally processed apple products and critically reviews both conventional and non-conventional methods used to inhibit this phenomenon.

Particular attention is given to the effectiveness of natural and synthetic antibrowning agents, as well as emerging processing technologies, with consideration of their impact on phenolic stability, antioxidant activity, and sensory quality. By emphasizing the potential of non-conventional treatments and combined approaches, the review identifies current limitations and future research directions in this field.

Importantly, publication A2 establishes a strong technological and quality-oriented framework for the experimental part of the dissertation. The issues discussed in this review directly justify the focus of the subsequent research on controlling enzymatic browning during impregnation, drying, and storage of apple products, thereby ensuring the coherence of the entire publication cycle.

Taken together, the two review papers demonstrate the candidate’s ability to critically synthesize extensive literature and to identify relevant research gaps; however, the main scientific contribution of the dissertation is provided by the original experimental studies discussed below.

The experimental core of the dissertation is represented by publications A3–A5, which together form a coherent and methodologically rigorous research cycle. These studies are logically connected, ensuring a continuous progression from concept development (A3), through process innovation (A4), to practical application and stability assessment (A5). Collectively, they are innovative, practically relevant, and scientifically robust, addressing the development of freeze-dried, bioactive-enriched apple products aimed at osteoporosis prevention and calcium supplementation.

Publication A3 (“Product development study of freeze-dried apples enriched with sea buckthorn juice and calcium lactate”) establishes the foundation by optimizing impregnation conditions to improve antioxidant capacity, calcium content, enzymatic activity, and sensory properties of freeze-dried Gala apples. Building on this, the application of advanced impregnation techniques—vacuum and ultrasound-assisted—in the following study enhances bioactive retention, calcium enrichment, and inhibition of enzymatic browning compared to conventional methods (A4, “Vacuum and ultrasound-assisted impregnation of Gala apple with sea buckthorn juice and calcium lactate”). The research cycle is



completed by a storage stability assessment, which evaluates functional, nutritional, and sensory properties over three months, confirming the practical potential of the developed product (A5, “Storage stability of bioactive-enriched freeze-dried Gala apples”).

Together, these studies combine systematic process optimization, innovative technological approaches, and comprehensive evaluation of physicochemical, enzymatic, nutritional, and sensory parameters. The findings provide clear guidance for industrial application and effectively bridge laboratory research with the development of functional foods addressing public health challenges.

Overall, the dissertation presents a logically coherent and methodologically sound body of work, demonstrating both scientific rigor and practical applicability, while setting the stage for a critical assessment of its **innovative aspects, limitations, and potential for further development**.

Despite the clear scientific merit and practical relevance of the dissertation, several points deserve critical consideration:

Realistic impact on osteoporosis prevention:

How might the forms of calcium used in the product (ascorbate, citrate), as well as their interactions with pectins and polyphenols, affect calcium bioavailability in the human body? What are the potential limitations of this functionality, and how could they be evaluated or improved in practice?

Given the likely small portion sizes of freeze-dried apple snacks in the diet, their actual contribution to calcium intake and osteoporosis prevention may be limited. This should be discussed in the context of public health relevance.

Suitability of the product form for the target population:

The crisp texture of the snack may pose difficulties for older adults with chewing or swallowing problems. Alternative formats, such as a mousse, puree, or fortified beverage, could be more accessible and better aligned with the needs of the intended consumers.

Cost and scalability considerations:

The production process, including impregnation, freeze-drying, and bioactive enrichment, may be relatively costly. It would be useful to discuss whether the expected health benefits justify these expenses and whether the process could be scaled up efficiently for industrial application.

In vitro vs. in vivo efficacy:

The antioxidant and calcium retention results were obtained in vitro. Further studies, including bioaccessibility, bioavailability, or human trials, are needed to confirm the functional benefits under real dietary conditions.

Long-term stability and sensory acceptance:

While the three-month storage study provides useful insights, additional discussion of longer-term shelf-life, packaging effects, and consistency of sensory attributes could strengthen the practical applicability of the findings. These points do not diminish the overall quality and significance of the work but provide constructive feedback that the candidate may consider during the defense or in future research.



Overall, the publications constituting the dissertation demonstrate a consistent focus on the development, functional evaluation, and storage stability of bioactive-enriched freeze-dried apples, highlighting the candidate's substantial contribution to the field of functional foods and human nutrition. The dissertation by MSc Marcellus Arnold is formally well-structured, methodologically sound, and scientifically robust. The combination of literature reviews and original experimental studies forms a coherent research cycle with clear practical relevance, while the constructive points noted above highlight areas for reflection and potential further development.

Final Conclusion

The reviewed doctoral dissertation by mgr Marcellus Arnold entitled „Innovative impregnation techniques and process optimization for shaping the physicochemical, functional, enzymatic, and sensory properties of freeze-dried apple snacks”, meets the requirements set out in Article 13, paragraphs 1–4 of the Act of July 20, 2018 – Law on Higher Education and Science (Journal of Laws 2023, item 742, with later amendments). Therefore, I hereby recommend that MSc Marcellus Arnold be admitted by the Scientific Council of the Faculty of Food Science and Nutrition at Poznań University of Life Sciences to proceed to the next stages of the doctoral examination process.



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