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## REVIEW

of the doctoral dissertation by Marcellus Arnold MSc

**EN: *Innovative impregnation techniques and process optimization for shaping the physicochemical, functional, enzymatic, and sensory properties of freeze-dried apple snacks***

**PL: *Innowacyjne techniki impregnacji i optymalizacja procesów w kształtowaniu właściwości fizykochemicznych, funkcjonalnych, enzymatycznych i sensorycznych liofilizowanych przekąsek jabłkowych***

prepared at the Department of Gastronomic Science and Functional Food, Faculty of Food Science and Nutrition, Poznań University of Life Sciences,  
Scientific supervisor: prof. dr hab. Anna Gramza-Michałowska.

*The review was prepared based on the letter dated October 28, 2025, issued by the Chair of the Scientific Council of the Food Technology and Nutrition Discipline at the Poznań University of Life Sciences, Prof. Dorota Cais-Sokolińska.*

The doctoral dissertation by Marcellus Arnold, MSc concerns the technological development, on a laboratory scale, of a functional and innovative apple snack enriched with antioxidants from sea buckthorn juice and calcium using the impregnation process.

In recent decades, there has been an increase in the incidence of non-communicable diseases, such as osteoporosis and other skeletal system disorders, caused by technological development and environmental pollution, resulting in completely different living and working conditions than before. Therefore, in the interest of public health, the WHO (World Health Organization), in its latest reports, recommends consuming about 400 g of edible fruits or vegetables daily to improve overall health and prevent nutrient deficiencies and diseases resulting from civilization changes. The growing health awareness of society is driving the popularity of plant-based food products with dedicated functional properties aimed at preventing deficiencies of selected nutrients. At the same time, in line with the current assumptions of achieving the UN Sustainable Development Goals, food should be produced naturally and locally, using technologies that do not cause environmental interference, and without the need for transportation or storage under special conditions—in other words, in a sustainable manner.

In this context, the Author's choice of raw materials for developing an innovative and functional food product, from the rich variety of fruits and vegetables available in Poland, is ideal. Apples were chosen as the base for the product under development — Poland is the fourth-largest producer of apples in the world. Apples contain compounds with antioxidant and anti-inflammatory properties. As an enriching source of minerals (anti-osteoporotic effect) and vitamins, sea buckthorn juice (*Hippophae rhamnoides*) was selected, which is cultivated in Poland with high efficiency and is considered a so-called *superfood*. To improve the quality of the developed food product, advanced techniques were tested and applied to prepare the raw material (apples) with functional additives (sea buckthorn juice, inulin, calcium lactate solution) under varying conditions. The effect of storage on selected quality indicators, including sensory attributes, was also examined. This research approach aligns with the implementation of selected UN Sustainable Development Goals: Goal 2 (elimination of hunger, improvement of food security and nutrition), Goal 3 (ensuring health and well-being), and Goal 12 (sustainable production and consumption).

### Formal Evaluation of the Dissertation

The PhD dissertation by Marcellus Arnold consists of two parts. The first part is the summary (autoreferat), in which the Author presented: • a list of publications included in the scientific dissertation along with information on research funding sources, • a summary of the work in Polish and English, • an introduction concerning the problem of preventing diseases related to calcium deficiency in the diet and potential techniques for preventing the decline in quality of food products based on locally available raw materials with high health-promoting potential (chapter 1), followed by • the aims and hypotheses (chapter 2). To illustrate the concept of the work and its subsequent stages, a diagram of the research activities, based on procedures described in articles A3–A5, which form the cycle of articles for this dissertation was presented. In the following chapters, the Author: • presented the research methodology (materials & methods) (chapter 3), and • provided a detailed research findings (chapter 4), shown as confirmation of the formulated hypotheses in three successive stages of research work. Last chapter (5) of this dissertation part contains • conclusions and practical implications of the thesis.

The second part of the dissertation consists of the full versions of the publications forming the basis of the doctoral dissertation (five articles – A1 to A5) and statements regarding the co-authors' contributions to each publication.

The scientific achievement forming the basis for Marcellus Arnold's application for the doctoral degree comprises a cycle of five articles published between 2022 and 2025, entitled: **"Innovative impregnation techniques and process optimization for shaping the**

**physicochemical, functional, enzymatic, and sensory properties of freeze-dried apple snacks.”**

Two publications (A1 and A2) are review papers, in which the Doctoral Candidate is the first author, together with his scientific supervisor, prof. A. Gramza - Michałowska. The remaining three articles (A3–A5) are experimental studies in the field of food technology and constitute the scientific foundation for the innovative functional product presented in the dissertation. All publications appeared in journals listed in the JCR index and have an Impact Factor (IF) ranging from 2.3 (*Polish Journal of Food and Nutrition Science*, 2025) to 14.8 (*Comprehensive Reviews in Food Science and Food Safety*, 2022). The total number of points (according to The Polish Ministry of Science and Higher Education, MNiSW) for the publications presented as scientific achievements, list for the year of publication, is 640. These indicators demonstrate the very high level of scientific publications.

Based on co-authorships declaration's statements, the substantive contribution of Marcellus Arnold to the preparation of individual works can be considered leading and amounts to at least 80%. In each paper, the Doctoral Candidate was the author of the conceptualization, data curation, formal analysis, investigation, methodology, writing – original draft and review and editing. It is worth emphasizing that the research resulting in these publications was financed from projects obtained by the Doctoral Candidate: the PRELUDIUM grant funded by Polish National Scientific Centre, NCN – No. 2023/49/N/NZ9/00862, and two *Young Staff* grants in 2022 and 2023 funded by the Poznań University of Life Sciences.

**Therefore, I consider it justified for the Doctoral Candidate to present the publication cycle as a scientific achievement forming the basis for applying for the doctoral degree.**

The **summary (autoreferat)** constitutes a synthetic elaboration of the research results presented in the publication cycle indicated as the scientific achievement. The introduction to the publication cycle follows a typical structure for this type of work – as described above – and is additionally supplemented with diagrams showing the detailed course of experiments and methodology of subsequent research stages, which, in the era of the “visual society,” greatly facilitates understanding the concept and progress of the work. Personally, I consider this a very good formal approach, demonstrating the Doctoral Candidate's experience in presenting research results.

Chapters of the summary were prepared based on information collected and research results published in the cycle of five articles constituting the scientific achievement, as well as on 51 literature references (listed in the *References*), which include the latest publications on the discussed topic, emphasizing its importance. These also include other publications co-authored by the Doctoral Candidate that were not included in the cycle; publications by other team members concerning the technological development of new and enriched food products

and the determination of their health-promoting properties; and current reports and studies by institutions involved in food control and shaping public nutrition perception.

Drawing knowledge from literature resources and collaborators indicates an extremely broad and in-depth approach by the Doctoral Candidate to the research problem, which involves seeking optimal technological solutions – a highly valuable effort in the era of sustainable economy.

**Therefore, the choice of the dissertation topic by the Doctoral Candidate should be considered justified from a scientific, cognitive, and application perspective.**

**The research aims and hypotheses** of this dissertation are presented in chapter 2 of the summary and reflect the tasks carried out in the experimental articles A3–A5.

The main goal of the research was to evaluate the physicochemical, functional, enzymatic, and sensory properties of freeze-dried apples (Gala variety) enriched with antioxidant compounds from sea buckthorn juice and calcium through the impregnation process, as a potential functional snack that may help prevent osteoporosis and increase calcium intake. The Author preceded the definition of the main objective with the testing of three hypotheses concerning the developed functional product and the technology of its enrichment, which were correctly and positively confirmed because of completing the specific tasks:

**H1a and H1b:** The antioxidant properties, calcium content, nutritional value, browning enzyme activity, and sensory characteristics of freeze-dried apple products are significantly influenced by temperature, time, and the composition of impregnation solutions containing different concentrations of sea buckthorn juice, inulin (H1a), and calcium lactate (H1b) (tasks 1 and 2 presented in publications A3 and A4).

**H2:** The use of vacuum impregnation and ultrasound-assisted impregnation has a significant effect on the physicochemical and functional properties (antioxidant properties, calcium content) as well as the browning enzyme activity of freeze-dried apple products (task 2 in publication A4).

**H3:** The functional properties, enzymatic browning, and sensory characteristics of freeze-dried products change during storage; however, their antioxidant properties, calcium content, and sensory attributes remain acceptable after three months of storage (task 3 presented in publication A5).

The **research methodology** was presented along with references to detailed information in the individual publications for each stage of the study.

However, in Chapter 3 of the summary – materials and methods, the description of the carotenoid extraction process for quantitative determination using chromatographic methods was missing. These analyses were performed for stages 1 and 3 of the study for sea buckthorn

juice and apple products before and after impregnation. Fortunately, the detailed extraction procedure was described in the full versions of publications A3 and A5.

The main technological task in the thesis was the selection and optimization of the preservation (and enrichment) process for a food product highly susceptible to enzymatic browning (presence of polyphenol oxidase, PPO). The characterization of methods used in the industry was collected and described in detail in article A2. For practical application during the development of the functional product, the Author selected an innovative impregnation method under normal atmospheric pressure conditions, as well as vacuum impregnation (IV) and ultrasound-assisted impregnation (US), which he refined to optimal conditions in subsequent stages of the work (articles A3, A4, A5), also modifying the impregnation solution (concentration of sea buckthorn juice and calcium lactate solution), temperature, and immersion time. The description of the optimization of the impregnation process in successive stages shows the significant conceptual and technological contribution made by the Doctoral Candidate at this stage of the work.

In addition, to assess the content and activity of antioxidant compounds and to determine the quality parameters of the tested samples, instrumental analytical methods were used (liquid chromatography, spectrophotometric methods, atomic absorption spectroscopy), which require laboratory proficiency. For the evaluation of sensory attributes, the profiling method was applied with the participation of a trained panel. Performing the planned research in three stages using the described methods is very time-consuming and deserves emphasis.

Among the more interesting data analysis methods applied were:

- in stage 1, the Response Surface Methodology (RSM) was used to determine the effect of impregnation solution composition and other process factors influencing the antioxidant properties of freeze-dried apples during impregnation;
- in stage 3, multiple linear regression (MLR) and principal component analysis (PCA) were used to assess the interactions of individual antioxidant factors.

The drawback of regression techniques is that they only allow one to confirm the existence of relationships, but not to prove the existence of a causal link underlying these relationships. The use of exploratory methods (such as PCA) to analyse the connections between these factors is better. However, for the presented data, I would recommend using correspondence analysis, which is related to factor analysis (such as PCA) but better illustrates the relationships between the studied product (subjected to technological processing) and its sensory characteristics.

The methodological approach to research related to the optimization of the impregnation process and storage studies, as well as the use of a wide range of measurement and analytical methods for antioxidant and sensory characterization of samples obtained in successive stages, deserves recognition.

The **discussion of results** was presented concisely and clearly in chapter 4 of the summary, based on the findings published in articles A3–A5 from the cycle of publications constituting the scientific achievement. For each stage of the research, the most important discoveries were summarized, and confirmation of the successive hypotheses (described in detail earlier) was indicated. Presenting the data from the publication cycle in this way demonstrates the cause-and-effect sequence in the Doctoral Candidate’s work, providing a clear and transparent picture of scientific achievements while emphasizing the most significant contributions.

On page 18 of the summary, the Author, in describing the results obtained for stage 3 of the work, refers twice to the PCA factor plot for the characterization of the IMP sample in terms of bioactive compound content and sensory attributes, which, however, was not included in this summary. It appears in the original publication A5.

Chapter **conclusions and practical implications** summarize the dissertation and highlights its application-oriented character. The Author pointed, the most important conclusions regarding the optimization of conditions for preparing (freeze-drying) and impregnating apples, as well as the composition of the impregnation solution, to obtain products with improved functionality—higher calcium and fiber content, minimal loss of antioxidants, reduced PPO/POD enzymatic activity, high crispness, and acceptable sensory properties.

The Author also indicated the limitations of the conducted research—focusing exclusively on *in vitro* analysis of the obtained freeze-dried apple products. He proposed further research, including both *in vitro* and *in vivo* experiments, to assess the bioavailability of antioxidants and calcium contained in the developed product, storage experiments aimed at determining the shelf-life, and improvements in sensory properties (taste) before preparing the product for introduction to the consumer market.

### Questions, Comments, and Remarks

After analysing the PhD dissertation by Marcellus Arnold, MSc, I can state that the publications included in the cycle present a high substantive level and constitute a collection of interesting studies that do not require more comments. The summary was prepared carefully, although with some omissions, which I mentioned earlier.

As a reviewer, I would like to present several questions and comments that arose during reading:

- what criteria did the Author consider when selecting Gala apples for the experiment involving the development of a snack impregnated with sea buckthorn juice and calcium lactate? Were these technological or economic considerations?
- was the extraction efficiency of polyphenolic compounds and carotenoids evaluated for the tested products and raw materials (juice)? I am particularly interested in the assessment of extraction efficiency for solid samples (plain snacks and impregnated snacks).

- currently, in the literature on production process control and food quality—especially for products with high sugar and polyphenols content — fingerprint and non-destructive methods are gaining increasing importance. These methods are fast and precise. Among them are near-infrared (NIR) and infrared (IR) spectroscopies. They can be used to monitor changes in parameters such as antioxidant activity (anthocyanin or carotenoid pigment content) or other physicochemical characteristics that change during product development. It may be worth considering their application in the process of product optimization control, even on a laboratory scale. These are efficient control methods that ensure non-destructive analysis, reduce chemical reagent costs, and enable data digitization for rapid multivariate analysis. The use of such quality control methods is one of the elements of sustainable production.

### Summary

The doctoral dissertation entitled *“Innovative impregnation techniques and process optimization for shaping the physicochemical, functional, enzymatic, and sensory properties of freeze-dried apple snacks”* by Marcellus Arnold, enters the scope of agricultural science and the discipline of food technology and nutrition.

The form of the dissertation adopted by the Author undoubtedly required careful planning and execution of research within a limited timeframe, enabling the publication of results in journals. The cycle of publications included in the dissertation proves that the Doctoral Candidate successfully achieved this goal. The summary (autoreferat) presents the outline of successive stages of the work in a concise and illustrative manner, which also indicates the Author’s high level of organization and ability to present experimental results effectively. Based on the demonstrated co-authorship declarations of individual publications, it should be acknowledged that the Author demonstrated the ability to use scientific achievements in the field of his interest. The publication cycle, presenting successive stages of research, is well and logically planned, allowing the Doctoral Candidate to consistently achieve the set objectives.

The evaluated dissertation has high scientific value as well as practical applicability. Therefore, it can be expected that the innovative apple snack, after conducting additional studies indicated by the Author in chapter 5, will be ready for introduction to the consumer market. From a substantive perspective, I assess the work highly, and the minor remarks mentioned earlier do not affect its scientific value.

It is also worth emphasizing that Marcellus Arnold (ORCID: 0000-0002-1749-8592), during his doctoral studies, demonstrated exceptionally intensive scientific activity, as evidenced by: participation in conferences and internships (3 conferences and 4 short-term internships), publication activity (13 publications outside the cycle included in the dissertation),



and the implementation of research projects funded by Polish National Scientific Centre (NCN) and the Poznań University of Life Sciences.

The acquired scientific and practical laboratory experience resulted in an extremely interesting, well-developed, and highly practical doctoral project, which I read and evaluated with great pleasure.

**After reviewing the doctoral dissertation submitted for evaluation by Marcellus Arnold, MSc, I hereby confirm that it fully complies with the statutory requirements for doctoral theses as stipulated in Article 187 of the Act of July 20, 2018, Law on Higher Education and Science (Journal of Laws of 2018, item 1668, as amended). Therefore, I formally request the Scientific Council of the Food Technology and Nutrition Discipline at the Poznań University of Life Sciences to admit Mr. Marcellus Arnold to the subsequent stages of the doctoral procedure.**

*Katarzyna Pasulski-Lewko*

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Poznań, December 22, 2025

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### Recommendation for Distinction

The evaluated dissertation is an exceptionally relevant work from a technological perspective — modern methods of food production and quality improvement, as well as from a social perspective — prevention of skeletal system diseases.

It constitutes a collection of comprehensive studies forming a coherent project, with the dominant contribution of the Doctoral Candidate in their implementation. The quality of the obtained results is confirmed by their publication in five international journals with a high IF; the publications forming the dissertation have a cumulative **Impact Factor = 33.3**.

The tasks outlined in the research objectives were successfully accomplished by the Author. The research results and the conclusions drawn from them represent a significant contribution to the discipline of food technology and nutrition and undoubtedly possess application value. The Author also demonstrated the ability to undertake a highly relevant research problem, conduct experiments, engage in scientific discussion, and draw substantively correct conclusions, which deserves recognition and attests to the high scientific level of the Doctoral Candidate.

Therefore, I submit to the Scientific Council of the Food Technology and Nutrition Discipline at the Poznań University of Life Sciences a request to **grant distinction** to the doctoral dissertation by Marcellus Arnold entitled: *“Innovative impregnation techniques and process optimization for shaping the physicochemical, functional, enzymatic, and sensory properties of freeze-dried apple snacks”*, prepared at the Department of Gastronomic Science and Functional Food under the scientific supervision of prof. Anna Gramza-Michałowska.

