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Zaprojektowanie innowacyjnego aktywnego materiału opakowaniowego o właściwościach przeciwdrobnoustrojowych

Designing an innovative active packaging material with antimicrobial properties

Abstract

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In the modern world, innovations are a key driving force of economic development and have a decisive impact on building a competitive advantage of every organization. Last years have shown that in the field of product innovations, solutions that are part of the sustainable development policy are emphasized.

A clear increase in research focused on the search for new packaging materials is dictated not only by market needs, but also by legal requirements imposed on both producers and consumers of new materials. Innovations in this area build a clear competitive advantage on the market of manufacturers of packaging materials. Many research works are devoted to the search for new raw materials or sustainable functional additives for packaging, favouring the creation of new active packaging functions or strengthening the existing ones, and at the same time, due to their biocompatibility, biodegradability, and lack of toxicity. Literature data indicate that the use of naturally occurred additives as an active substance may have a positive effect on the properties of packaged food, extending food storage time and shelf life.

The description of the literature part of the work began with the presentation of the theoretical aspects of innovation management, considering the models of the innovation process. The first models of innovation development date back to the 1970s. They became the foundations for the development of the next ones, used in the modern economy. It is important to note that most models of the innovation process are based on products and processes of the private sector, and to a lesser extent focus on development in the public sector. The models described in the work distinguish certain stages, phases, components, or main activities. These phases or stages have their order, but not in the case of every model it is linear. The model developed by Cooper in the 1970s was one of the first to have the most characteristic and ordered phases. It also indicates the starting point of the next one, which can only start when the project meets all the requirements. This linear approach undoubtedly has its advantages, as it gives the opportunity to determine whether the project should be continued or not. Many of the later models also recognize the crucial role of feedback, which cannot be overlooked during the development of innovation. In the models developed in the early 21st century, which are much less linear, the role of these feedbacks is emphasized. In the latest models, a significant role is played by phases or stages that take place after launching - introducing innovations to the market. This entails maintaining innovation, and even reintroducing it and increasing its scale. The Snijders model also includes a phase of

explicit learning - it is not only getting to know the innovation itself, but also how the innovation process itself was carried out. This phase is of key importance for practitioners in the implementation of subsequent projects, but very often it is not performed in a structured manner. In addition to the basic phases in the innovation process, there are models that view the innovation process not only in a vacuum, but also taking into account the context of the environment. Context factors include both organizational nature, social factors and current trends that must be considered in the innovation process to ensure its effective and efficient implementation.

The next part of the work was devoted to the characteristics of packaging dedicated to contact with food. The analysis of the types of used materials shows the advantages and disadvantages of individual solutions, also indicating the direction of further development of the packaging sector. Functional, active, and intelligent packaging, which is more widely known, used, and appreciated by consumers, is described, which, in addition to its basic features assigned to the packaging, provide the consumer with additional benefits, information or other advantages while maintaining the high quality of the product. Packaging materials were characterized, the task of which is to extend the shelf life of food products by influencing the processes occurring in food. Starting from the role of emitters or absorbers of individual substances, to packaging with antimicrobial properties and the characteristics of active additives that determine this feature in packaging. An important aspect in this regard is the role of particular types of nanoparticles such as nanosilver, nanoclays or nanogold and their use in the packaging industry, which is the subject of the further part of the theoretical study included in the work. The use of nanoparticles offers an opportunity to reduce food spoilage and waste. Many consumers, due to the lack of information about the condition of packaged food, throw away products that would still be suitable for consumption. Often, a small deviation from the norm, be it colour, consistency or even the expiry of the best-before date, leads to the fact that products end up in the bin, and the use of appropriate functional packaging could reduce this phenomenon.

In the further part of the work, legal regulations regarding packaging intended for contact with food are discussed, the problem of food waste and the assumptions of the sustainable development policy are presented as essential elements to be considered during the process of designing innovations in the packaging sector. The requirements of the

European Green Deal, which currently set the directions for the development of packaging materials, were also taken into account. The problem of reducing the amount of waste and food waste is also mentioned here. Every year, every inhabitant of our continent throws away an average of 150 kg of food, and the main reason for this is exceeding its use-by date. These aspects determine the trends and directions of innovation development that determine market success.

The theoretical part of the work ends with a chapter devoted to the possibility of using nanoparticles in food packaging. The advantages of using packaging with the addition of nanoparticles such as gold, silver, clay or iron and their benefits for the packed product as well as the inhibition of the development of microflora were presented. This chapter also covers methods of synthesis, focusing, among others, on green methods of obtaining nanomaterials, which are gaining increased popularity in recent years. In addition, the methods of chemical and structural characterization of nanoparticles that were used in the practical part of the work were also described. The chapter ends with an analysis of the nanoparticles market, which shows the growing development of this sector, indicating, however, the requirements that must be met when introducing a new material to the market, while acting as a factor inhibiting this market and protecting from the point of view of health safety and environmental impact.

The selection of an appropriate innovation management method determines the achievement of success. Therefore, the implementation of the research part of the work began with the development of an innovation development model dedicated to active packaging with antimicrobial properties. This model was developed based on literature data and appropriately adapted to the environment of the packaging industry sector. The model has 5 basic stages (Fig. 1), for which detailed research tasks have been assigned (Table 1).

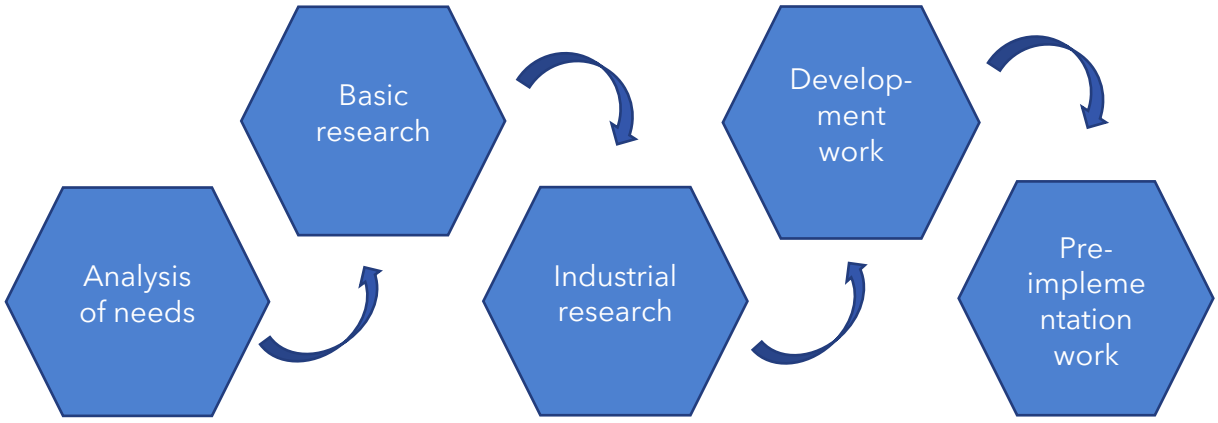

Fig. 1 Developed model of the innovation process

Source: own elaboration

Table 1. Detailed research tasks of developed model of the innovation process

Analysis of needs	**Basic research**	**Industrial research**	**Development work**	**Pre-implementation work**
Basic guidelines: - Legal regulations - Food waste - Assumptions of sustainable development policy Consumer research Market expectations in the field of antimicrobial packaging	Literature research Biosynthesis, characterization, and evaluation of the activity of iron preparations	Development of the active coating application methodology Testing the functionality of active packaging materials in laboratory conditions	Production of prototype active packaging materials Testing the functionality of prototypes in operational conditions	Determining the level of technological readiness

Source: own elaboration

The analysis of market needs showed a clear trend in the search for environmentally friendly, biodegradable packaging materials and biocompatible. In addition, natural ingredients are becoming increasingly popular, which can be a kind of additive, creating an

active layer in the structure of packaging. This layer can have a beneficial effect on the properties of food, extend its shelf life, which translates not only into economic profits for food producers, but also to reduce the process of food waste. The conducted consumer research showed a positive attitude of respondents to the development of innovations in the field of active packaging, acceptance of a potential increase in the price of the final product and the need to expand knowledge about the properties of active packaging. At the same time, an analysis of available market research conducted over the last two years was performed, which confirmed the agreement of the respondents in terms of the questions asked to them and trends regarding the development of innovation in the field of active packaging with antimicrobial properties.

The guidelines obtained based on the analysis of market needs and literature studies carried out in basic research prompted the start of research aimed at developing a methodology for the synthesis of natural preparations with antimicrobial activity based on iron and oregano extract. The preparations obtained in this way were subjected to a thorough analysis. Using electron microscopy techniques (TEM - transmission electron microscopy and STEM - scanning transmission electron microscopy), the morphology of the obtained particles was determined, and the use of the EDX method (energy dispersive X-ray spectroscopy) allowed to analyse their elemental composition. The obtained results showed the presence of zero-valent iron agglomerates and iron oxides. Then, the antimicrobial activity of the obtained iron preparations against selected microorganisms such as *Salmonella sp., Listeria sp*. and *Escherichia coli* was assessed. It turned out that the preparations inhibit the development of individual microorganisms to a different extent, without affecting the inhibition of the development of the desired probiotic microflora of the *Lactobacillus* genus. The obtained results allowed the transition to the next stage of the model - industrial research.

At this stage of the research, iron preparations were suspended in a varnish approved for contact with food and applied as an active layer to the surface of two types of substrates - foil and parchment. A crucial element was to determine the concentration of the iron preparation and the optimal thickness of the obtained coatings to maintain the durability and activity of the obtained packaging materials. The obtained prototypes of packaging materials made it possible to proceed to development work, which was the next stage of the developed model, and to carry out storage tests in which cottage cheese was used as a product subject

to microbiological deterioration. Samples of cheese packed in prototype packaging were stored for 4 weeks in refrigerated conditions, and their microbiological and sensory quality was assessed at weekly intervals. The conducted storage tests allowed to confirm the influence of the prototype active packaging on inhibiting the development of microorganisms on the surface of the tested cheese and delaying the process of the appearance of unfavourable sensory changes.

The last stage of the developed model of the innovation process was the performance of pre-implementation works. Technological readiness expressed on a nine-point scale was set at level seven - a prototype of the technology was demonstrated in operational conditions. The manufacturer made a prototype of the packaging in a serial version, and on this basis, the cost calculation of the packaging production was carried out, which ends the stage of pre-implementation work.

The conducted literature analysis and empirical research allow the following conclusions to be drawn:

1. The developed and adopted model of the innovation process enabled the development of a prototype of a new product - an active packaging material with antimicrobial functionality intended for food. Thanks to the technique used, it was possible to combine the issues of the innovative process for the production sector, paying attention to the requirements and legal regulations accompanying enterprises when implementing a new product, but considering scientific and laboratory work.
2. Consumer research confirmed the most common reason for throwing away food by households - symptoms of spoilage, as well as showed a positive attitude of respondents to the development of innovation in the field of active packaging and acceptance of a potential increase in the price of the final product.
3. Preparations containing iron agglomerates obtained by biosynthesis using oregano extract showed antimicrobial activity against pathogenic bacteria and food spoilage microorganisms, without inhibiting the development of lactic acid bacilli.
4. The designed innovative active packaging material showed effectiveness in delaying the process of microbiological spoilage of food, which in turn has a significant impact on the quality and safety of the packaged food product. Storage tests

showed high effectiveness in inhibiting the development of microorganisms on the surface of the packed product.

5. Performing tests of the prototype active packaging material in operational conditions allows us to determine its technological readiness at level 7.

Product innovations in food packaging are a principal element determining the development of the packaging industry. However, considering the applicable legal regulations, the assumptions of the sustainable development policy and market trends, the design of new packaging materials in this sector is currently a considerable challenge. The developed model of the innovative process made it possible to obtain a prototype active packaging with antimicrobial functionality. The packaging material made of biodegradable materials and natural components has found interest on the market of food producers, which contributed to the start of its commercialization process.