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ZITA MARKEVIČIŪTĖ

CREATION OF A BIODEGRADABLE PAPER-BASED PACKAGING MATERIAL WITH ADDITIVES ENHANCING BIODEGRADABILITY IN THE CONTEXT OF THE CIRCULAR ECONOMY

DOCTORAL DISSERTATION

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KAUNAS UNIVERSITY OF TECHNOLOGY

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Technological Sciences, Environmental Engineering (T 004)

2025, Kaunas

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KAUNO TECHNOLOGIJOS UNIVERSITETAS

ZITA MARKEVIČIŪTĖ

BIOLOGIŠKAI SKAIDŽIOS POPIERIAUS PAGRINDO PAKUOTĖS MEDŽIAGOS SU SKAIDUMĄ SKATINANČIAIS PRIEDAIS SUKŪRIMAS ŽIEDINĖS EKONOMIKOS KONTEKSTE

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LIST OF ABBREVIATIONS

BOD – Biological oxygen demand;
BMP – Biomethane potential;
CD – Cross direction;
CH_4 – Methane;
CTMP B15 – Chemithermomechanical pulp with wheat bran 15wt% filler;
CTMP B15Y – Chemithermomechanical pulp wheat bran 15wt% filler and yeast additive;
CTMP B40 – Chemithermomechanical pulp with wheat bran 40wt% filler;
CTMP B40Y – Chemithermomechanical pulp wheat bran 40wt% filler and yeast additive;
CTMP W15 – Chemithermomechanical pulp with grain by-products 15wt% filler;
CTMP W15Y – Chemithermomechanical pulp with grain by-products 15wt% filler and yeast additive;
CTMP W40 – Chemithermomechanical pulp with grain by-products 40wt% filler;
CTMP W40Y – Chemithermomechanical pulp with grain by-products 40wt% filler and yeast additive;
CTMP Y – Chemithermomechanical pulp with yeast additive;
CTMP – Chemithermomechanical pulp;
COD – Chemical oxygen demand;
EU – European Union;
FCMs – Food Contact Materials;
FSC – Forest Stewardship Council;
GHG – Greenhouse Gas;
GMP – Good Manufacturing Practices;
LCA – Life Cycle Assessment;
MD – Machine direction;
NBSK – Northern bleached softwood kraft pulp;
NBSK B 40 – Northern bleached softwood kraft pulp with wheat bran 40wt% filler;
NBSK B 40Y – Northern bleached softwood kraft pulp with wheat bran 40wt% filler and yeast additive;
NBSK B15 – Northern bleached softwood kraft pulp with wheat bran 15wt% filler;
NBSK B15Y – Northern bleached softwood kraft pulp with wheat bran 15wt% filler and yeast additive;
NBSK loop – Northern bleached softwood kraft pulp closed loop sheet-former method;
NBSK W15 – Northern bleached softwood kraft pulp with grain by-products 15wt% filler;
NBSK W15Y – Northern bleached softwood kraft pulp with grain by-products 15wt% and yeast additive;
NBSK W40 – Northern bleached softwood kraft pulp with grain by-products 40wt% filler;

NBSK W40Y – Northern bleached softwood kraft pulp with grain by-products 40wt% and yeast additive;
NBSK Y – Northern bleached softwood kraft pulp with yeast additive;
NBSK Y loop – Northern bleached softwood kraft pulp closed loop sheet-former method with yeast additive;
OECD – Organisation for Economic Co-operation and Development;
PE – Polyethylene;
PFAS – Polyfluoroalkyl substances;
PLA – Polylactic Acid;
PVOH – Polyvinyl alcohol;
SC – Saccharomyces cerevisiae;
TS – Total solids;
VS – Volatile solids.

INTRODUCTION

The relevance of the problem

Food and packaging are part of the everyday products we consume. Increasing use of packaging materials has led to a rise in packaging waste. Paper and plastics are the major materials used in the packaging industry, including single-use packaging. According to Eurostat data, in 2022, Lithuania generated 151.12 kg of packaging waste per inhabitant. In comparison, the EU average was 186.66 kg per inhabitant[1]. As presented in **Figure 1**, the primary material for packaging waste in both the EU and Lithuania was paper and cardboard, accounting for 34.0 million tonnes or 40.8% of the total packaging waste stream at the EU level, and 148.5 thousand tonnes or 34.7% in Lithuania[2]. This was followed by plastic, which constituted 16.2 million tonnes (19.4%) in EU and 107 thousand tonnes (25%) in Lithuania[3].

Globally, production of plastics reached 413.8 million metric tonnes in 2023[4], including single-use packaging, accounting for approximately 36.5% of this production[5]. In parallel, the growing trends of digitization and increased consumption have driven a rise in paper packaging, which reached a total of 258.74 million metric tonnes in 2023[6].

Single-use packaging, commonly used for on-the-go eating, takeaways, and meal deliveries, has become integral to our modern lifestyles. According to Statista[7], the European meal delivery market is projected to reach 45.38 billion Euros in 2025, growing to over 50.9 billion Euros by 2029. The growing demand for convenience has led to a rise in single-use packaging, which poses a significant environmental challenge.

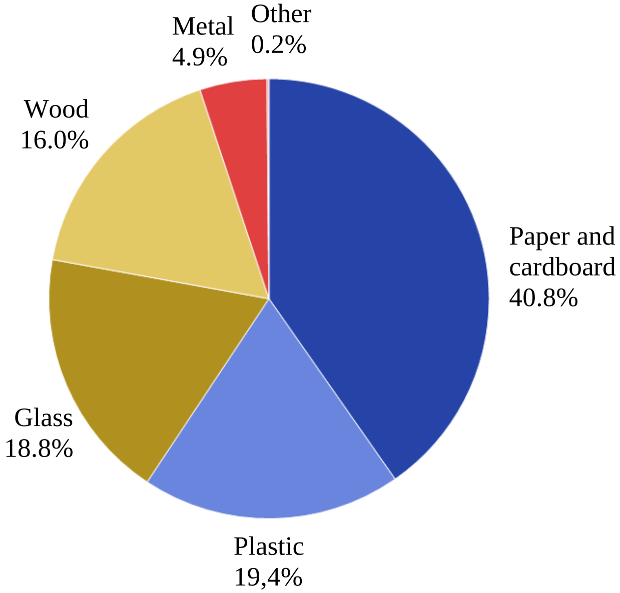

Fig. 1. Packaging waste generated, by packaging material, EU, 2022 (%)

Despite the effort to recycle, packaging recycling rates in the EU vary significantly by material. In 2022, the recycling rate for paper and cardboard packaging in the EU was notably high at 83.1%. In Lithuania, the recycling rate for paper and cardboard packaging was similarly high at 81.1%[8]. In contrast, the recycling rate for plastic packaging was significantly lower, standing at 40.7% at the EU level and 44.1% in Lithuania[9].

Meanwhile, globally only 9% of plastic waste are recycled[10]. The majority of plastic waste, approximately 79%[11], accumulates in landfills, oceans, and other parts of the ecosystem, causing ecological damage and loss of biodiversity[12] [13] [14].

In response, the EU has implemented a range of measures to mitigate the environmental impact of single-use plastics. These initiatives include bans on specific single-use plastic items, as well as mandates to enhance recycling efforts and improve waste management practices. By implementing these policies, the EU aims to combat plastic pollution and accelerate the shift toward more sustainable and environmentally friendly packaging alternatives. Specific targets include the separate collection and incorporation of recycled plastic content[15], a 50% recycling rate for plastic packaging by 2025, and a 55% rate by 2030. Additionally, the targets include a 75% recycling rate for paper and cardboard packaging by 2025 and an 85% rate by 2030[16]. In addition to these targets for plastic, paper and cardboard recycling, the broader circular economy framework recognizes the importance of organic recycling. Directive (EU) 2018/851 explicitly encourages organic recycling, including composting and anaerobic digestion, as complementary to mechanical recycling[17]. These processes play a crucial role in reducing waste, restoring soil health, and generating renewable energy. Furthermore, the EU Bioeconomy Strategy[18] highlights the significance of biological cycles in closing material loops, ensuring that biodegradable materials are effectively reintegrated into natural systems rather than being lost as waste. Integrating both technical and biological cycles, the circular economy approach maximizes resource efficiency and minimizes environmental impact. This approach is also reflected in Lithuanian national policy, as outlined in the “Lietuvos pramonės perėjimo prie žiedinės ekonomikos kelrodis”[19] (National Action Plan for the Circular Economy). This document identifies recycling, including biological recycling, as a priority area for developing a cleaner and more competitive industry that aligns with the needs of a sustainable future economy.

Minimizing packaging waste has become a key objective in sustainable development. This could be achieved by applying circular economy principles, emphasizing optimal and efficient raw material selection as well as sustainable resource management. Additionally, optimizing packaging end-of-life and mitigating negative environmental impacts, such as visual pollution and microplastic contamination in the value chain, are crucial[20].

The growing demand for convenience, combined with the environmental concerns associated with single-use packaging made from conventional plastics, has intensified the need for sustainable raw material alternatives. However, developing food packaging from conventional plastic alternatives comes with several critical challenges.

First, the selection of sustainable materials is paramount for conserving natural resources and reducing environmental impacts. This requires identifying materials that are renewable, biodegradable, or mechanically recyclable while maintaining the functional performance required for effective packaging. Second, ensuring the barrier properties of food packaging poses a significant challenge, particularly in relation to its end-of-life management. Barrier properties are essential to protect food from moisture, oxygen, and other external factors that could compromise its quality and safety. At the same time, these properties must be achieved in a way that does not hinder the recyclability or compostability of the packaging, ensuring it aligns with circular economy principles and contributes to sustainable waste management practices.

The use of bioplastics, as one of the possibilities, derived from renewable sources[21]. These materials can significantly reduce dependence on fossil fuels and lower carbon footprints[22]. Bioplastics already offer versatility in the food and catering segment, with products ranging from cups and trays to plates and cutlery available in both single-use and reusable forms[23]. Replacing conventional plastics with bioplastics could also substantially reduce greenhouse gas emissions and microplastic pollution, with potential savings of 241 to 316 million tonnes of CO_2 equivalent per year[24] .

Paper packaging from sustainable forests is another viable alternative. Advanced paper production technologies allow for reduced environmental impacts of the paper industry and optimization of raw materials, energy, and water consumption[25]. The use of non-wood fibers, such as those derived from agricultural by-products like cereal, rice straw, wheat straw or wheat grain by-products[26], offers additional environmental benefits[27]. By repurposing materials that would otherwise be treated as waste, the paper industry can lower its dependence on wood fibers, thereby reducing deforestation and preserving natural forests. Additionally, incorporating agricultural by-products into paper production decreases fossil fuel consumption, offering a more sustainable alternative that aligns with circular economy principles. These agricultural by-products are abundant and do not require additional land for cultivation, making them a highly efficient raw material source for paper production. Exploring these sustainable alternatives, the food packaging sector can work towards reducing its environmental impact while meeting the growing demand for convenient and safe food packaging solutions.

There are several end-of-life challenges for single-use packaging. To meet barrier property requirements, traditional plastic food packaging often comprises multiple material layers, complicating mechanical recycling[28]. Even mono-material packaging, if contaminated with food, becomes unrecyclable due to the degradation of overall material quality, which is critical for the recycling process.

Uncoated paper is both biodegradable and recyclable; however, it lacks necessary barrier properties required for food packaging, such as resistance to moisture, grease, and oxygen, which are essential to preserve food quality and safety[29] [30], thus food packaging is often coated to improve oil, water and oxygen barrier properties. The most commonly barrier coatings used in paper based food packaging are made of fossil fuel resources, such as polyethylene (PE), polyvinyl alcohol (PVOH), polyfluoroalkyl substances (PFAS)[31] [32]. These materials provide essential moisture and grease resistance but raise environmental concerns due to their persistence and potential for microplastic pollution.

Fossil-coated paper, although capable of meeting food packaging requirements, poses environmental challenges as it is neither mechanically recyclable nor biodegradable, contributing to microplastic pollution. Conventional plastic-coated paper packaging, particularly those utilizing PE or other non-biodegradable polymers, contributes to microplastic pollution at usage stage[33] [34] and end of life stage[35] [36]. During degradation, mechanical forces, UV radiation, and chemical interactions fragment these coatings into microplastics, which persist in ecosystems. These microplastic particles pose risks to aquatic and terrestrial environments, bioaccumulating in food chains and potentially impacting human health.

PVOH, unlike PE, is considered biodegradable under specific environmental conditions; however, incomplete degradation in natural environments raises concerns about its potential contribution to microplastic pollution[37]. If PVOH does not fully mineralize into CO_2, water, and biomass, residual microplastic-like fragments may enter ecosystems, challenging its classification as an entirely sustainable alternative[38]. Understanding the degradation pathways and optimizing conditions for complete PVOH breakdown is crucial to mitigating unintended environmental consequences.

On the other hand, paper coated with biodegradable coatings is also mechanically unrecyclable[39] when food-soiled due to the low quality of its fibers. Therefore, food-contaminated paper with biodegradable coatings is best directed toward biological recycling processes, such as composting[40] to minimize its environmental impact and ensure alignment with circular economy principles.

The aim and objectives

The aim of the dissertation is to create a biologically degradable material for single-use fast food packaging, aligned with the principles of the circular economy, made exclusively from renewable raw materials and additives that promote biodegradability, and to analyze its environmental performance as well as its physical-mechanical and biodegradation parameters.

The objectives of the research are as follows:

1. Define the environmental performance criteria for single-use fast food packaging by assessing the origin of raw materials, recyclability, and biodegradability. Identify and evaluate optimal bio-based alternatives and coatings to replace conventional fossil-based components.

2. Create a biodegradable packaging material prototype by integrating renewable bio-based raw materials and additives that enhance biodegradability while ensuring the necessary mechanical and barrier properties for food packaging applications.

3. Investigate the physical-mechanical and barrier properties of the created packaging prototype and conduct comprehensive aerobic and anaerobic biodegradation tests to assess its end-of-life performance.

4. Evaluate and integrate the research findings to assess the environmental performance, physical-mechanical characteristics, and biodegradation efficiency of the created packaging material, ensuring its contribution to circular economy integration in both – raw material selection and packaging waste management stages.

Thesis statements:

1. In the production of single-use paper food packaging, up to 40% of primary wood pulp can be substituted with non-wood agricultural by-products. This approach promotes industrial symbiosis and significantly reduces the reliance on virgin raw materials, contributing to resource efficiency and sustainability.

2. The incorporation of *Saccharomyces cerevisiae* (baker's/brewer's yeast) enhances the barrier properties of the created single-use food packaging material while improving its biodegradation efficiency.

Research object and methodology

The research object is a biodegradable fast food packaging material that aligns with circular economy principles and is created using renewable bio-based raw materials – wheat bran and wheat grain processing by-products. The dissertation analyzes the possibility of partially replacing primary wood pulp with non-wood agricultural by-products and investigates the effect of *Saccharomyces cerevisiae* used as a functional additive, on the material's barrier properties and biodegradability.

The applied experimental methodology includes raw material preparation, laboratory sheet formation, testing of physical–mechanical and barrier properties, as well as aerobic and anaerobic biodegradation assessments and the analysis of the obtained results to evaluate the environmental performance of the created material and its potential integration into circular material flows.

Scientific novelty and practical value

This dissertation presents an innovative scientific approach to the creation of biodegradable single-use food packaging materials by integrating non-wood agricultural by-products and *Saccharomyces cerevisiae* (baker's/brewer's yeast) into paper-based composites. The research introduces novel insights into single use food packaging material design through the following key contributions:

1. Substitution of primary wood pulp with non-wood agricultural by-products. The study demonstrates that up to 40% of virgin wood pulp fibers can be replaced with non-wood agricultural by-products, promoting industrial symbiosis and enhancing the circularity of the material while maintaining its structural integrity and functional performance.
2. Functional application of *Saccharomyces cerevisiae* in biodegradable packaging. The research evaluates *Saccharomyces cerevisiae* as a bio-based additive, assessing its impact on barrier performance and biodegradation efficiency, an area with limited prior investigation in the field of packaging materials.

3. Creation and validation of a biodegradable packaging material. The study presents an experimentally validated biodegradable paper-based material prototype that achieves a balance between mechanical durability, barrier functionality, and biodegradability, offering a viable alternative to conventional plastic-coated paper packaging in line with circular economy principles.

Practical value

The practical value of this dissertation lies in its contribution to biodegradable single-use food packaging materials, offering an alternative to fossil-based and/or plastic-coated paper packaging. The study provides insights into material formulation, biodegradation and functional properties, which can serve as a basis for further industrial research and development.

Key contributions to industry and circular economy:

Raw material utilization and circularity. The research demonstrates the lab-scale feasibility of incorporating non-wood agricultural by-products as an alternative to virgin wood pulp, contributing to resource efficiency and industrial symbiosis in packaging production.

Elimination of fossil-based coatings. The created material demonstrates potential as a biodegradable alternative to plastic-coated paper packaging, with compatibility for biological recycling systems, including industrial composting and anaerobic digestion. However, further optimization of barrier properties is required.

Potential for industrial adaptation. While the study is based on lab-scale prototypes, the results provide a scientific foundation for optimizing material compositions that could be further adapted to industrial processes.

Material and resource efficiency benefits. The use of locally available agricultural by-products promotes by-products valorization and supports regional economies creating alternative applications.

Compliance with strategies and legal regulation. The created packaging material prototype aligns with both the European Union and national policy and strategies related to plastic reduction, the application of circular economy principles, and the transition toward environmentally friendly packaging solutions.

Papers and co-authors' contributions to papers

The thesis is based on 4 scientific articles:

1. MARKEVIČIŪTĖ, Zita; VARŽINSKAS, Visvaldas. Smart material choice: the importance of circular design strategy applications for bio-based food packaging preproduction and end-of-life life cycle stages // *Sustainability*. Basel: MDPI. ISSN 2071-1050. 2022, vol. 14, iss. 10, art. no. 6366, p. 1-13. DOI:10.3390/su14106366.

Contribution of authors:

Markevičiūtė, Z.: original idea and the theoretical aspects of the paper, data collection and preprocessing, methodology, writing – original draft preparation.

Varžinskas, V.: methodology, writing – review and editing.

2. MARKEVIČIŪTĖ, Zita; VARŽINSKAS, Visvaldas. Plant-origin feedstock applications in fully green food packaging: the potential for tree-free paper and plant-origin bio-plastics in the Baltic Sea region // *Sustainability*. Basel: MDPI. ISSN 2071-1050. 2022, vol. 14, iss. 12, art. no. 7393, p. 1-15. DOI: 10.3390/su14127393.

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3. MARKEVIČIŪTĖ, Zita; LYYTIKÄINEN, Johanna; LEMINEN, Ville; VARŽINSKAS, Visvaldas. Grain byproducts and *Saccharomyces cerevisiae* application in paper packaging material: impact on physical–mechanical and barrier properties // *Discover sustainability*. London : Springer Nature. ISSN 2662-9984. 2024, vol. 5, art. no. 82, p. 1-16. DOI: 10.1007/s43621-024-00257-8.

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4. MARKEVIČIŪTĖ, Zita; GUERRESCHI, Arianna; MENIN, Glauco; MALPEI, Francesca; VARŽINSKAS, Visvaldas. Wheat bran and *Saccharomyces cerevisiae* effect on aerobic and anaerobic degradation efficiency of paper composite // *Microorganisms*. Basel: MDPI. ISSN 2076-2607. 2024, vol. 12, iss. 10, art. no. 2018, DOI: 10.3390/microorganisms12102018.

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Malpei, F.: aerobic and anaerobic testing methodology, writing – review and editing, supervision.

Varžinskas, V.: writing – review and editing.

1. SCIENTIFIC LITERATURE AND LEGAL REQUIREMENTS FOR FOOD PACKAGING REVIEW

1.1. Connecting circular design, industrial symbiosis and end-of-life strategies

The food packaging life cycle comprises five key stages: preproduction (including material selection, design, and refinement), production, distribution (transport, storage, and packaging), product use, and disposal[41]. Before reaching the end-of-life phase, circular strategies such as reuse and remanufacturing can extend product lifespans. When a product is no longer usable in its original form, end-of-life strategies, including mechanical and biological recycling, incineration, and landfilling, determine whether materials are reintegrated into the circular economy or permanently removed from the material cycle.

Among the stages of a products life cycle, the preproduction phase—focused on material selection—has the most significant impact[42]. Studies estimate over 80% of manufacturing costs[43] and up to 80% of environmental impacts[44] are determined during the design phase, underscoring the crucial role of circular design in optimizing material flows. The European Commission's Sustainable Product Policy and Ecodesign framework[45] further reinforces this by emphasizing that product design dictates resource efficiency, longevity, and recyclability, making it a key driver in reducing material and energy consumption while promoting closed-loop systems.

Integrating ecodesign principles ensures that products are not only functionally efficient but also align with circular economy objectives, reducing waste and energy consumption while promoting closed-loop material cycles. Similarly, waste management significantly affects environmental outcomes across various categories[46], emphasizing the interdependence of material selection and end-of-life strategies.

Circular strategies, often summarized as the "3R's"[47] (reduce, reuse, and recycle) play a central role in waste and resource management hierarchies. These principles are deeply integrated into the product life cycle. The Waste Management Hierarchy outlined in the Waste Framework Directive (Directive 2008/98/EC)[48] prioritizes reducing environmental and health impacts through efficient recycling. Zero Waste Resources Management Hierarchy[49] incorporates broader considerations, such as changing consumption habits, rethinking business models, and prioritizing waste-free product designs.

The circular economy integrates circular product design and waste management strategies and is defined as a systems-based solution to address global challenges such as climate change, biodiversity loss, waste, and pollution. Within this framework, transitioning the fast-moving consumer goods sector to circular practices requires a regenerative design approach, as highlighted in the Circular Design Guide by the Ellen MacArthur Foundation in collaboration with IDEO. This guide outlines six essential circular design strategies[50] that provide a roadmap for sustainable and innovative product development:

Product as a service: Shifting from ownership to access through leasing models.

Embedded intelligence: Enhancing user experiences with integrated smart technologies.

Product life extension: Encouraging repairs, upgrades, or remanufacturing before recycling or disposal.

Smart material choices: Selecting materials that ensure durability, functionality, recyclability, and integration of recycled content.

Closed loop systems: Facilitating the collection, reuse, and recycling of used products.

Modularity: Designing products to enable easy replacement of parts and reuse in other applications.

Two of these strategies – smart material choices and closed-loop systems – are directly applicable to food packaging.

Smart Material Choices. At the preproduction stage, selecting appropriate single-use packaging materials directly supports two of three circular strategies:

- Reduce: Minimizing material use while optimizing performance;
- Recycle: Ensuring materials are compatible with mechanical or biological recycling processes. The choice of material significantly influences the viability of end-of-life treatments and helps retain materials within circular flows.

Closed Loop Systems. Establishing collection and recycling systems for used packaging supports resource recovery and reduces waste.

Closed-loop systems also exemplify industrial symbiosis, which refers to the collaborative engagement of traditionally separate industries to enhance competitive advantage through the physical exchange of materials, energy, water, and by-products. This approach emphasizes synergistic interactions between firms, fostering eco-innovation and promoting the efficient use of resources[51].

1.2. Integrating circular strategies in food packaging

Circular product design focuses on minimizing environmental impact throughout a product's life cycle. Key strategies include reducing material use, designing for reuse or recyclability, and selecting materials compatible with biological recycling. Industrial symbiosis complements these efforts by reutilizing by-products from other industries, creating resource-efficient systems. End-of-life strategies, such as mechanical and biological recycling, ensure that packaging materials remain in circulation, reducing waste accumulation.

The diagram (**Figure 2**) highlights how circular economy principles, such as reduce, reuse, and recycle, align with specific stages of the product lifecycle, particularly preproduction and disposal, and how these stages influence sustainable material management. By showcasing these interrelationships, the diagram serves as a visual tool to enhance understanding of how strategic decisions in design and material selection can promote circularity, minimize waste, and optimize resource efficiency in food packaging systems. Circular economy strategies, product life cycle stages, circular design strategies, and resource management hierarchy stages relevant to single-use food packaging are highlighted in red.

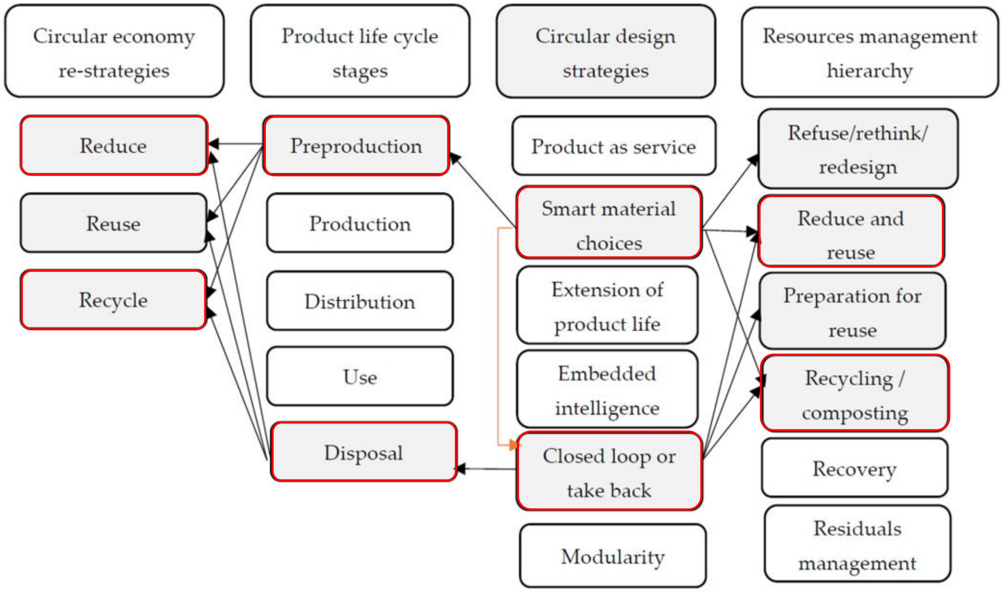


Fig. 2. Connections between circular economy principles, product design strategies, and the resource management hierarchy in relation to the preproduction and disposal stages of the food packaging lifecycle [20]

1.3. Smart material choice: wood and non-wood fibre packaging materials

1.3.1. Paper as single-use packaging material

Key single-use packaging parameters and added values that can lead to the most significant positive environmental impacts emphasize the use of renewable resources or/and by-products. These materials have lower environmental impacts and contribute to reducing fossil fuel consumption, microplastic pollution, and greenhouse gas emissions compared to materials derived from non-renewables[52] [53] [54]. Additionally, bio-origin materials are generally biodegradable, reducing their persistence in the environment and bringing additional benefits to the biological cycle.

As mentioned, key circular economy strategies for single-use food packaging include reducing material usage and designing for recyclability, ensuring that materials can be either mechanically recycled or composted at the end of their life cycle. These approaches help minimize waste, enhance resource efficiency, and support long-term sustainability[55]. The most significant environmental benefits in food packaging are realized when these strategies are implemented using renewable raw or secondary materials.

Paper remains the most extensively utilized material in the packaging industry, valued for its versatility, renewability, and recyclability. Derived primarily from wood pulp, global production of wood pulp reached approximately 195.79 million metric tonnes in 2022, up from 193.82 million metric tonnes[56].

The production of packaging paper and board has experienced consistent growth, with global output reaching 249 million tonnes in 2020. In Europe, member countries of the Confederation of European Paper Industries (CEPI) reported a total paper and board production of 90.2 million tonnes in 2021[57], reflecting the expansion of the EU economy and increased consumption of fast-moving consumer goods.

Paper and board can be manufactured from wood pulp, non-wood pulp (fibers, such as sugarcane bagasse, wheat straw, kenaf, cotton rags, and hemp), or a combination of various fibers. Pulp is categorized into virgin fibers (primary pulp) and recycled fibers (secondary pulp).

Paper is well-suited for single-use fast food packaging for several reasons:

Sustainability: Paper is renewable, biodegradable, and/or recyclable, making it an environmentally friendly option compared to plastic-based alternatives.

Customization: Paper can be easily shaped to meet the diverse requirements of fast food packaging, offering flexibility in design.

Cost Efficiency: The widespread availability of raw materials and mature production technologies make paper packaging cost-effective for large-scale use.

Consumer Preference: With growing consumer awareness of environmental issues, paper packaging is often viewed as a greener, more responsible choice, aligning with market demand for sustainable packaging.

Regulatory Compliance: As governments worldwide push for reductions in plastic waste, paper packaging offers a compliant solution for businesses seeking to adhere to these regulations.

These factors, combined with the growing demand for sustainable packaging options, have solidified paper's position as the material of choice for single-use fast food packaging. Its balance of functionality, environmental benefits, and adaptability makes it the leading material in this sector.

1.3.2. Locally available non-wood fiber paper potential

The transition to sustainable single-use packaging is closely linked to the adoption of materials that effectively balance functionality with environmental benefits. Selecting the right raw materials is critical. Utilizing regionally abundant agricultural by-products (in this case those found in the Baltic Sea region), can significantly reduce the environmental footprint by lowering transportation emissions, as these materials can be sourced locally[58].

The production of paper from non-wood fibers, especially from non-dedicated crops, not only reduces deforestation but also lowers associated carbon emissions, thereby contributing to a more sustainable packaging industry[27]. The total land in the Baltic Sea region countries used to harvest potential wood fibre alternatives and plant-origin plastic feedstock in 2020 was 7.3 million hectares[27]. As indicated in **Table 1**, wheat production volumes in Lithuania alone reached 4,482,760 tonnes in

2022, indicating a high availability of wheat by-products (bran) and agricultural production by-products as feedstock for use in non-wood fiber paper packaging.

Table 1. Wood fibre alternative feedstock in Lithuania, 2022

Feedstock	Item	Unit	Value
Area harvested	Rye	ha	29470
Production	Rye	t	71090
Area harvested	True hemp	ha	580
Production	True hemp	t	1350
Area harvested	Wheat	ha	946720
Production	Wheat	t	4482760

Source: FAOSTAT[59]. Crops and livestock products data.

In 2021, Lithuania produced approximately 6.37 million metric tonnes of wheat by-products, accounting for about 85% of the country's total cereal crop by-products[60]. This substantial volume highlights the significant potential for utilizing wheat by-products, such as straw and bran, in various applications, including sustainable packaging materials.

Wheat bran, a by-product of the milling process, serves as another valuable source of non-wood fiber feedstock. Its production volume is determined by the quantity of wheat processed and the extraction rate during milling. Given Lithuania's substantial wheat production, it can be inferred that the country generates a considerable amount of wheat bran. This by-product offers promising opportunities for various industrial applications, including the development of biodegradable packaging solutions.

As mentioned, paper and board can be made entirely from wood pulp, 100% non-wood pulp, or a blend of different fibers. Plants with high cellulose and low lignin content are the most suitable for its production. Data indicates that blending non-wood fibers into wood pulp (10–15%) can enhance paper properties without disrupting the papermaking process[61]. The the end-use paper properties depend on the treatment method, fibre source, fibre cheical composition, and fibre properties. Chemical composition (%) of wood and non-wood materials is provided in **Table 2**.

Table 2. Chemical composition (%) of wood and non-wood materials

Material	Cellulose	Hemicellulo	Lignin	Reference
Wood	50	20–25	30–35	[62]
Hard wood	40–44	15–35	18–25	[63]
Soft wood	40–44	20–32	25–35	[63]
Willow	50	19	25	[63]
Thermo-mechanical pulp	56	22.15	25.6	[64]
Chemical thermo-mechanical pulp (CTMP)	52	24.51	16.33	[64]
Bleached softwood kraft pulp (BSKP)	87	16.07	1	[64]

Unbleached softwood kraft pulp (UBSKP)	87	16.94	2.6	[64]
Hemp fiber (USO 31)	78.4–81.7	5.7–6.4	10–13	[65]
Hemp fiber (Fedora 17)	65.6–84.9	6–8.1	2.7–4.5	[65]
Hemp fiber (Felina 34)	64–83	11–15	1–4	[65]
Hemp fiber (Fibrimon 56)	53.2	6.9	5	[65]
Hemp hurds (untreated)	44.5	32.78	21.03	[66]
Hemp hurds (treated)	53.87	12.06	27.27	[66]
Hemp hurds (treated)	45.7	31.05	24.22	[66]
Flax	62.21–74.01	13.91–22.30	2.56–7.96	[67]
Wheat straw	28–39	23–24	16–25	[68]
Wheat bran (untreated)	8.56–11.1	27.3–33	3–4.1	[69]
Wheat bran (treated)	29.6	24.9	-	[69]
Wheat bran (treated H2)	35	6.83	-	[69]
Small grains(wheat and rye by-products)	10–20	15–25	5–15	[70]
Oat straw	30–35	25–30	12–20	[71]
Buckwheat husks	28–35	20–25	12–16	[72]

Plants with high cellulose and low lignin content are ideal for pulp production, as these properties enhance fiber processing and paper quality. Mechanical or chemical treatments can enhance cellulose content and agricultural fiber properties, these processes tend to be more energy- and chemical-intensive. For example, untreated wheat bran has a lower cellulose content of 8.56–11.1%. Chemical treatments, such as NaOH or H_2SO_4, can increase the cellulose content of wheat bran to 29.6% and 35%, respectively, making it more suitable for industrial applications. Despite the benefits of chemical enhancement, untreated agricultural by-products remain a more sustainable choice, as they require less energy and fewer resources during processing. Therefore, using untreated feedstock is a more sustainable alternative[73].

1.3.3. Wheat production by-product applications in food packaging

Wheat production by-products hold significant potential for sustainable food packaging applications, offering an eco-friendly alternative to traditional petroleum-based and wood-pulp materials. These by-products are locally (Baltic sea region and Lithuania) abundant, renewable, and economically viable feedstocks for packaging production.

Wheat bran, with its fiber-rich composition, could be particularly well-suited for creating biodegradable materials for single-use food packaging, aligning with circular economy principles. Similarly, wheat straw and other by-products, rich in cellulose, are essential for producing paper and bioplastics. Utilizing these materials in packaging could significantly reduce reliance on virgin wood pulp while repurposing agricultural waste, thereby diverting it from landfills. Additionally, these by-products can help lower greenhouse gas emissions and conserve resources by enabling the production of biodegradable or recyclable packaging solutions.

Despite the promising potential of wheat bran and wheat grain by-products in sustainable packaging applications, few scientific studies have comprehensively explored their use. One study[74] by Ravshanbek S. Alibekov et al. examined the utilization of wheat components such as starch, gluten, and fiber in creating biodegradable packaging. The study discussed fabrication processes like solvent casting and extrusion, highlighting their effectiveness in enhancing food shelf life and quality while addressing challenges such as moisture content and interfacial adhesion in composites.

Another study[75] by A. Shaji George and A. Hovan George focused on the application of wheat bran, rice bran, and corn starch as raw materials for biodegradable tableware and packaging products. It explored manufacturing processes, properties, applications, and ecological impacts, showcasing the potential of these materials to replace conventional single use products.

The use of cereal by-products, including wheat straw and bran, in eco-friendly packaging was emphasized in research[76] by Gaurav Kr Deshwal et al. This study highlighted the importance of characterizing these by-products for economic packaging applications and discussed innovations in their utilization. Similarly, a study[77] by Pedro Souza Filho and colleagues investigated wheat lignocellulosic by-products, such as straw and bran, for producing bio-based materials suitable for packaging. This research underscored the co-production approach, enhancing the economic viability of using these by-products.

These studies underscore the potential of wheat by-products as sustainable alternatives to conventional materials, showcasing their suitability for various biodegradable and eco-friendly packaging applications. However, there is a significant lack of research specifically focused on utilizing wheat grain production by-products in paper composite food packaging. Therefore this gap highlights an area for further exploration, offering an opportunity to develop innovative, sustainable solutions that leverage these locally abundant by-products to enhance the environmental and economic performance of the packaging industry.

1.4. Closed-loop: single-use paper packaging end of life in circular economy

1.4.1. Mechanical and biological recycling

A closed-loop system is central to the circular economy, ensuring that materials remain in circulation as long as possible, reducing waste and the demand for virgin resources. Recycling, whether mechanical or biological, plays a pivotal role in achieving this goal, especially for single-use food packaging, where reuse is often impractical.

Mechanical recycling offers a favorable end-of-life option by significantly lowering energy inputs compared to using primary resources, thus positively impacting the greenhouse gas (GHG) balance. For instance, recycling single-use plastic could reduce CO_2 emissions by up to 90%[78]. Enhanced recycling rates, such as achieving 35% in the fast-food sector, could cut packaging emissions by 16%, with further reductions possible if packaging incorporates recycled content[79]. Despite these benefits, mechanical recycling faces challenges such as limited capacity, poor sorting infrastructure, and contamination from food waste.

Biological recycling, such as composting and anaerobic digestion, offers an alternative for biodegradable and bio-based materials. Biodegradable packaging, particularly for food-related applications, captures additional value by diverting food waste and contaminated packaging from landfills. This not only reduces environmental plastic pollution[80] but also simplifies waste management by eliminating food-soiled contaminants from mechanically recyclable streams. Although composting is CO_2 neutral[22], it can yield biogas in digestion processes, further enhancing GHG savings.

Biodegradable packaging adds co-benefits by facilitating the separation of food waste and improving the overall recycling process. For example, industrially compostable PLA films used in fruit and vegetable packaging prevent food contamination in recycling streams[81], making mechanical recycling more efficient. However, the application of biodegradable packaging should focus on cases where biodegradability adds clear value, such as managing food-contaminated waste streams. The Ellen MacArthur Foundation's butterfly diagram[82] provided in **Figure 3** is crucial in understanding the integration of the biological cycle into the mechanical cycle within the circular economy.

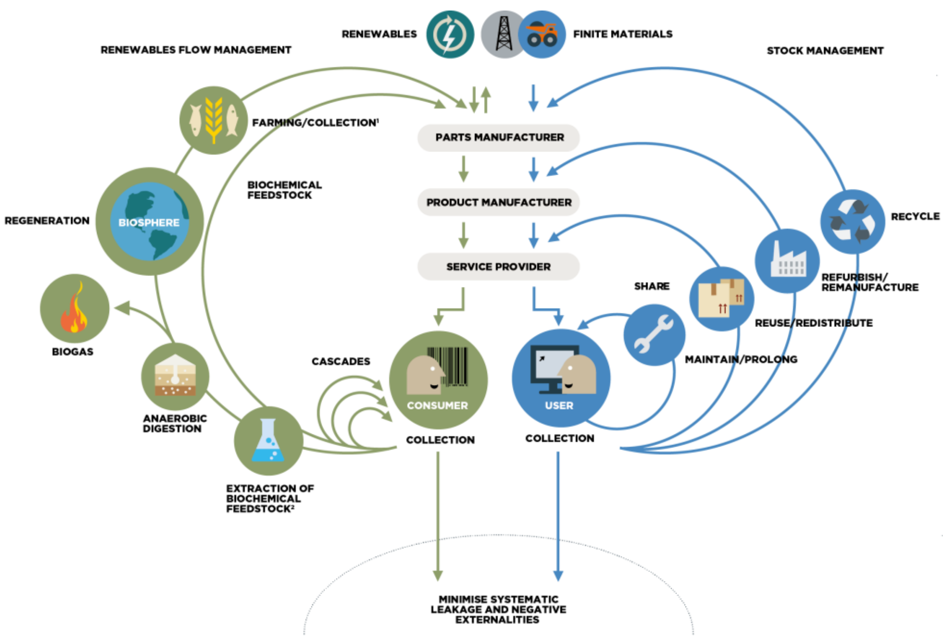


Fig. 3. The butterfly diagram: visualising the circular economy[82]

The diagram illustrates how biological materials, like biodegradable packaging, can circulate through the economy, returning nutrients to the soil and supporting natural systems, while technical materials, such as metals and plastics, are kept in use through reuse, refurbishment, and recycling. This integration ensures that materials flow efficiently and sustainably through both biological and technical cycles, maximizing their value and minimizing waste[83].

Biological cycles are vital in reducing environmental impacts through biodegradable food packaging. It helps cleanse waste streams and divert food waste from landfills, thereby reducing methane emissions and other environmental pollutants[65]. Furthermore, such packaging returns biomaterials to the soil, enhancing biological recycling and contributing to soil health and fertility[84]. Biodegradable food packaging offers additional values:

A solution for non-recyclable packaging: It provides an effective solution for packaging materials that are not suitable for mechanical recycling processes, thereby reducing the volume of waste that ends up in landfills[85].

Capturing and diverting food waste: Biodegradable packaging can capture food by-products and divert organic waste from landfills and incineration to composting facilities, significantly reducing greenhouse gas emissions from decomposing food waste[86].

Simplified consumer experience and cleaner recycling streams: By using biodegradable packaging, consumers can dispose of food waste and its packaging together, simplifying waste separation and improving the quality of recycling streams by reducing contamination with non-biodegradable materials.

Supporting biological cycles of the circular economy: Biodegradable packaging supports the biological cycles within a circular economy by returning nutrients to the soil, thus closing the loop on organic material cycles and enhancing sustainability.

1.4.2. Packaging coatings and recyclability

Paper packaging coatings play a critical role in meeting the barrier requirements for fast food packaging while directly influencing the material’s recyclability and lack of biodegradability[87 88 89]. While the barrier requirements for fast food packaging are generally less stringent than those for long-term food storage, they remain crucial for maintaining the quality and safety of food during short periods of consumption.

Barrier coatings can complicate recycling processes by hindering the separation of fibers during mechanical recycling or reducing the material's biodegradability in biological recycling systems. Fossil-based coatings, such as polyethylene (PE), polyvinyl alcohol (PVOH), polyfluoroalkyl substances (PFAS) are widely used in paper packaging to provide effective barriers against moisture and grease, essential for maintaining food quality and safety in food applications. However, these coatings present significant challenges in recycling processes[90 91 92]. The strong adhesion between the fossil-based layer and paper fibers complicates their separation, often rendering the packaging unsuitable for mechanical recycling. This difficulty in separation can lead to contamination of the paper recycling stream, reducing the quality of recycled paper products. Moreover, the persistence of these conventional plastic coatings in the environment contributes to microplastic pollution, posing ecological risks.

Biobased coatings, such as those derived from PLA or other renewable materials, offer a more sustainable alternative. While some biobased coatings can be compatible with mechanical recycling streams if properly separated, they are particularly advantageous for biological recycling, as they can compost alongside the paper fibers under industrial composting conditions. Bio-based packaging coating materials have gained prominence due to their environmental benefits[93] and renewable nature. A wide range of bioplastics and bio-coatings, including starch-based, protein-based, and cellulose-based[94] materials, is currently undergoing research. Common feedstocks for starch-based materials include wheat, rice, barley, oats, corn, and beans[95]. Protein-based bio-coatings are primarily derived from sources such as gluten, soy, pea, corn zein, whey, casein, collagen, and gelatin[96].

Starch-based coatings are appreciated not only for their biodegradability but also for their widespread availability, making them a viable option for certain food packaging applications. These coatings are typically derived from sources like corn, potato, or wheat. However, starch-based coatings also encounter significant challenges related to mechanical properties, flexibility, and resistance to water vapor and gases[97]. Because of their hydrophilic nature, starch-based coatings tend to absorb moisture readily. This high moisture permeability restricts their use in applications requiring strong barrier properties. To mitigate these issues, starch-based materials can be tailored to improve their functional properties[98] [99] [100], enhancing their appeal for sustainable packaging solutions. Researchers are exploring various modifications, such as blending with hydrophobic substances like polyvinyl alcohol (PVOH)[26], combining with chitosan for improved oil resistance[101] employing chemical and enzymatic modifications or incorporating nanoparticles[102]. These modifications aim to enhance the mechanical strength, flexibility, and barrier properties of starch-based coatings, making them more suitable for a wider range of packaging applications.

Protein-based coatings are recognized for their high biodegradability and film-forming capabilities, which can offer effective barrier properties against oxygen and aroma compounds[103], making them suitable for specific food packaging needs.

Despite these benefits, protein coatings face challenges related to water vapor and gas resistance. Proteins are naturally hydrophilic, resulting in coatings that are highly permeable to moisture. This characteristic limits their effectiveness in applications where moisture barrier properties are crucial. For example, although protein-based films can provide strong oxygen and aroma barriers, their poor resistance to moisture can lead to swelling and compromised mechanical integrity in humid environments.

Different protein-based resources have been investigated for their ability to form bio-films and coatings, including silk protein[104], whey protein[105] [106] [107], soy / soybean protein isolate[108] [109] [110] [111], wheat gluten protein[112], egg-white protein[113]. *Saccharomyces cerevisiae,* commonly known as baker's yeast, is also rich in protein, containing approximately 50% of its dry weight as protein[114] [115]. However, it has not been investigated as extensively as other protein resources for film and coating applications. This under exploration presents an opportunity for the research to fully utilize its potential in bio-based biodegradable paper packaging coatings.

1.4.3. Saccharomyces cerevisiae application in bio-coating

Saccharomyces cerevisiae (SC), commonly known as baker's yeast, is widely studied and utilized due to its rich nutritional profile and functional properties. SC is the dominant yeast used in the production of alcoholic beverages such as beer, wine, and spirits[116]. With its high protein content and favorable amino acid profile, SC is not only a valuable dietary supplement[117] or functional food[118], but also offers promising characteristics for developing sustainable and functional bio-coatings. Moreover, cells of *Saccharomyces cerevisiae* can be regarded as a low-cost, abundant, and food-grade ingredient, making it suitable for food contact packaging and bringing benefits such as improved soil quality[119] at the end of life if the packaging is composted.

Several studies show that SC has a notable ability to form biofilms[120] [121] [122] and adhere to a multitude of different surfaces[123], embedding in a self-produced extracellular matrix. Additionally, several studies have been published on biofilms made of SC biomass[124] [125] [126] [127]. There is evidence that SC could enhance coated paper packaging by impacting plastic degradation [128] [129] and microplastic removal[130]. Furthermore, a study demonstrates that yeast can be incorporated for the production of edible films[131].

Even though using SC for packaging barrier films represents an innovative approach that leverages biological processes for sustainable material development, there is no research focusing on wood-pulp paper or wood-pulp composites made with agricultural fiber fillers and their potential to form barrier coatings, nor their impact on the biodegradation of these materials.

1.5. Biodegradable fast food paper packaging functional properties and legislation

1.5.1. Key physical-mechanical and barrier properties

As the conducted literature analysis indicates, both wood and non-wood fiber-based food packaging, coated with bio-coatings, are bio-origin materials that, along with food waste and can be directed to the same composting streams without requiring separation. As indicated already, biodegradable food packaging adds significant value to the circular economy by simplifying waste management, cleaning waste streams, and capturing food waste to divert it from landfills. This approach integrates the biosphere into the circular economy cycle, enabling biomaterials to return to the soil through biological recycling. In doing so, it supports sustainable resource cycles and amplifies the environmental benefits of composting, fostering a more holistic and eco-friendly waste management system.

Fast food paper packaging requires specific characteristics to effectively protect food items and maintain their quality. It must meet defined physical, mechanical, and barrier property requirements to ensure food safety, durability, and functionality. The key physical, mechanical, and barrier properties are grammage (g/m²), thickness (µm), tensile strength (kN/m), tear resistance (mN), bending resistance (mN) and water contact angle (°). Air permeability is a less critical factor for fast food packaging, as it is significant for long shelf-life products where moisture control and gas exchange are essential to maintaining freshness and preventing spoilage.

Although exact specifications vary depending on the type of food and packaging design, **Table 3** provides approximate values for key properties commonly found in popular fast food packaging options, such as 125 g/m² grammage 250 g/m² grammage kraft paper cones[132] and take-out boxes[133].

Table 3. Approximate food packaging key propertie's values and descriptions

Property	**Approximate Value**	**Description**	**Reference**
Grammage (g/m²)	75–325	Weight per unit area; influences strength and durability.	Datasheet:[134] [135] [136]
Thickness (µm)	100–650	Determines rigidity and barrier capabilities.	Datasheet: [123] [124]
Tensile strength (kN/m)	MD: 7.9–15.6 CD: 4.5–8.5	Maximum stress the paper can withstand when stretched; indicates durability.	Datasheet: [122] [123]
Tear resistance (mN)	MD: 950–1830 CD: 1000–2100	Resistance to tearing; crucial for maintaining integrity during handling.	Datasheet: [122] [123]
Bending resistance (mN)	MD: 125–415 CD: 65–250	Resistance to bending; affects the ability to hold shape under load.	Datasheet: [123]
Contact angle (°) bio-coated	74.2–82.7	Measures wettability; influences resistance to liquids.	Publication [137]

MD – Machine direction; CD – Cross direction.

1.5.2. Biodegradable food contact packaging legislation

The food packaging industry in the European Union (EU) operates under a comprehensive regulatory framework that prioritizes both consumer health and environmental sustainability. Biodegradable fast food packaging is specifically engineered to meet diverse physical, mechanical, and barrier property requirements, which vary depending on the type of paper and its intended application. These properties ensure food quality and safety while supporting EU sustainability objectives.

The EU framework governs the entire lifecycle of packaging materials—from production to disposal—and establishes clear guidelines for both conventional and biodegradable packaging solutions. The regulatory framework and standards for food packaging in the EU cover multiple aspects, as summarized in **Table 4**.

Table 4. EU regulatory framework and standards for food packaging

Category	**Description**
Framework Regulation (EC) No. 1935/2004[138]	Ensures food contact materials (FCMs) do not release harmful substances or alter food characteristics. Requires traceability throughout the supply chain and mandates a Declaration of Compliance (DoC).
Good Manufacturing Practices (GMP) Regulation (EC) No. 2023/2006[139]	Establishes manufacturing standards to ensure safe food contact materials.
Heavy metal migration testing. Commission Regulation (EU) 2020/1245[140]	The regulation sets specific migration limits, authorized substance lists, and testing methods tailored to the properties of plastics. This regulation is not directly applicable to paper packaging or other non-plastic food contact materials. Safety assessments for paper packaging still follow general EU requirements under Framework Regulation (EC) No. 1935/2004.
General migration testing. Regulation (EU) No. 10/2011[141]	Covers the specific migration of substances from plastic materials and articles intended to come into contact with food. Regulation is not directly applicable to paper materials unless the paper includes a plastic layer or coating.
Recycled Materials. Regulation (EU) No. 2022/1616[142]	Regulation (EU) No. 2022/1616 specifies criteria for recycled plastics in food contact applications. Recycled paper undergoes rigorous safety assessments to meet EU standards.
EN 13432 Standards for compostable packaging[143]. Covers: Biodegradability (ISO 14855, ISO 14852); Disintegration (ISO 16929, ISO 20200); Ecotoxicity (OECD 208); Heavy Metal Limits (ISO 17088).	Requires compostable materials to biodegrade under industrial composting conditions without leaving toxic by-products. Biodegradability: ISO 14855 – aerobic biodegradation under controlled composting conditions. The material must biodegrade at least 90% compared to a reference material (e.g., cellulose) within 180 days. ISO 14852 – aerobic biodegradation in an aqueous medium. Requires at least 90% biodegradation within 6 months in controlled industrial composting conditions. Biodegradation is assessed by measuring the conversion of organic carbon into CO_2. Disintegration (optional): Specifies that the material must physically break down into small fragments (less than 2 mm) within 12 weeks. At least 90% of the packaging mass must disintegrate during this timeframe. Ecotoxicity: Ensures that the compost produced is free from harmful substances and supports plant growth. Tests involve growing plants in the compost to ensure no toxic effects are observed. Heavy Metal Content: Sets limits for heavy metals

	such as cadmium, lead, mercury, and chromium, ensuring these do not exceed harmful levels.
Waste Framework Directive (2008/98/EC)[144]	Promotes biological recycling as part of sustainable waste management strategies.
Circular Economy Action Plan[145]	Emphasizes integrating biodegradable packaging into food waste collection systems.
Sustainable Development Goals and A/RES/70/1 - Transforming our world: the 2030 Agenda for Sustainable Development[146]	Encourages the use of recyclable and biodegradable materials, aligning with environmental objectives.

Biodegradable uncoated paper packaging is regulated under the Framework Regulation (EC) No. 1935/2004, which ensures that food contact materials (FCMs) do not release harmful substances or alter the characteristics of food. This regulation mandates traceability across the supply chain and requires a Declaration of Compliance (DoC). Manufacturing processes must also adhere to the Good Manufacturing Practices (GMP) Regulation (EC) No. 2023/2006, ensuring safe and controlled production.

As uncoated paper is typically free from synthetic additives, it avoids the applicability of migration limits specified in Commission Regulation (EU) 2020/1245 and Regulation (EU) No. 10/2011, which focus on plastics and plastic-coated materials. Instead, uncoated paper follows safety assessments under general EU requirements, including heavy metal migration tests to ensure compliance with permissible levels for cadmium, lead, mercury, and chromium.

For compostable uncoated paper, compliance with EN 13432 standards is crucial. These standards require the material to achieve at least 90% biodegradation within six months and physically disintegrate into fragments smaller than 2 mm within 12 weeks. The resulting compost must be free of toxic by-products and support plant growth, aligning with sustainability goals outlined in the Circular Economy Action Plan and the Waste Framework Directive (2008/98/EC).

For coated / bio-coated paper food packaging, regulatory oversight includes both the paper substrate and the biodegradable coating. Like uncoated paper, it falls under the Framework Regulation (EC) No. 1935/2004 and the GMP Regulation (EC) No. 2023/2006, ensuring safety and quality throughout the production process.

If the coating contains bio-based polymers, compliance with EN 13432 standards is required to ensure the packaging is industrially compostable. Biodegradability and disintegration tests under ISO 14855 and ISO 16929, respectively, validate the material's breakdown in composting environments. Ecotoxicity tests confirm that the resulting compost is safe for the environment.

While Regulation (EU) No. 10/2011 and Commission Regulation (EU) 2020/1245 are not directly applicable to paper packaging, migration testing may be required for coatings to assess the transfer of substances to food. Recycled bio-coated materials must also meet strict safety standards under Regulation (EU) No. 2022/1616 to ensure they do not pose contamination risks.

1.6. Review summary conclusions

The conducted literature review revealed that the application of circular economy strategies is essential in addressing global challenges such as climate change, resource depletion, and waste management. A systematic approach to these strategies, including smart material choice by reducing raw materials and waste/resource management, ensuring that non-reusable products are recycled at the end of their life, is crucial, as it ensures that all stages of the food packaging life cycle are considered. This approach plays a vital role in the preproduction and disposal stages, directly influencing the environmental impact and end-of-life options for packaging materials.

The results of the theoretical overview showed that the selection of renewable materials is of paramount importance in mitigating negative environmental impacts and reducing reliance on fossil fuels. Paper, made from renewable resources and being the second most used material in the packaging sector, is considered a much more sustainable choice. However, paper production, heavily reliant on wood fibers, has raised concerns over forest depletion and sustainability due to the rising demand for packaging. The integration of non-wood fibers, particularly locally available agricultural by-products, is a way to reduce the need for primary raw materials and decrease waste production by implementing industrial symbiosis.

Further analysis of locally available materials in the Baltic Sea region identified wheat grain by-products as a particularly promising alternative to wood fiber. The use of wheat production by-products and other agricultural by-products in paper production not only reduces pressure on forests but also presents environmental benefits at both the raw material and end-of-life stages. Tree-free paper made from these sources was found to significantly lower the carbon footprint and support the circular economy by facilitating biological recycling.

Despite these benefits, the overview revealed certain limitations and issues with paper packaging, particularly concerning barrier properties. Uncoated paper lacked the necessary oxygen and moisture barrier properties required for certain food packaging applications, limiting its use primarily to dry goods. The use of natural bio-coatings showed potential in enhancing the barrier properties of paper, making it more suitable for a wider range of food packaging applications.

The performed theoretical review led to the conclusion that a more sustainable paper packaging material could be developed as a composite, where up to 40% of the raw material is replaced with locally available wheat grain production by-products, such as wheat bran, and wheat grain production by-products. Additionally, a *Saccharomyces cerevisiae* bio-coating could be applied to enhance the barrier properties of the packaging.

2. RESEARCH METHODOLOGY

2.1. Overview

This chapter outlines the research methodology (see **Table 5**) used to create a biodegradable single-use food packaging material. The study was conducted in three distinct stages:

Stage I – literature review and data collection. Identification of the environmental performance criteria for biodegradable packaging. Evaluation of optimal bio-based alternatives through a systematic literature review and data analysis.

Stage II – physical-mechanical and barrier testing. Laboratory-based creation of a biodegradable paper composite material. Testing of its physical-mechanical and barrier properties, incorporating agricultural by-products and Saccharomyces cerevisiae.

Stage III – biodegradation assessment. Evaluation of the created material's biodegradability under controlled conditions. Assessment of aerobic and anaerobic degradation efficiency.

Table 5. Research stages and methodological framework

Stage	Objective	Paper
Stage I Literature review and data collection.	To define the key packaging parameters that can lead to the highest environmental impacts, integrate single use packaging into the circular economy; identify the best locally available biodegradable packaging feedstock.	Paper 1 – Smart material choice: the importance of circular design strategy applications for bio-based food packaging preproduction and end-of-life life cycle stages.
		Paper 2 – Plant-origin feedstock applications in fully green food packaging: the potential for tree-free paper and plant-origin bio-plastics in the Baltic Sea region.
Stage II Experimental research.	To create a biodegradable packaging material, test and analyze material physical-mechanical properties.	Paper 3 – Grain byproducts and *Saccharomyces cerevisiae* application in paper packaging material: impact on physical–mechanical and barrier properties.
Stage III Experimental research.	To test the aerobic and anaerobic biodegradability of the material prototype.	Paper 4 – Wheat bran and *Saccharomyces cerevisiae* effect on aerobic and anaerobic degradation efficiency of paper composite.

Stage I focused on identifying key parameters for creating fully green biodegradable packaging with significant environmental benefits while integrating single use packaging into the circular economy. A systematic methodology was employed to examine the integration of food packaging materials within the circular economy, with a particular emphasis on material selection and waste management strategies. The literature review encompassed the circular economy, circular product design, and waste/resource management strategies, with a particular focus on the role of food packaging within these contexts. Relevant literature was identified using keywords such as “circular economy strategies”, “circular product design”, “circular food packaging”, and “waste management strategies”. The sources included databases such as Scopus, ResearchGate, ScienceDirect, and Google Scholar, along with reports from organizations like the Ellen MacArthur Foundation, European Bioplastics, and Zero Waste Europe.

Stage II focused on the experimental development of a biodegradable packaging prototype utilizing selected materials, including wood pulp, wheat grain fillers, and *Saccharomyces cerevisiae* as an additive. This stage involved testing the prototype’s physical and mechanical properties and was conducted at the School of Energy Systems, Department of Mechanical Engineering, Lappeenranta-Lahti University of Technology (LUT) in Lappeenranta, Finland.

Stage III advanced to further experimental research by testing the aerobic and anaerobic biodegradability of the material prototype. The aerobic biodegradation testing was conducted at the DICA LIA Laboratory, Politecnico di Milano in Milan, Italy, while anaerobic biodegradation testing took place at the Environmental Engineering A. Rozzi Laboratory – FabE-lab in Cremona, Italy.

The stage-by-stage relationship connections of the work shown in **Figure 4**.

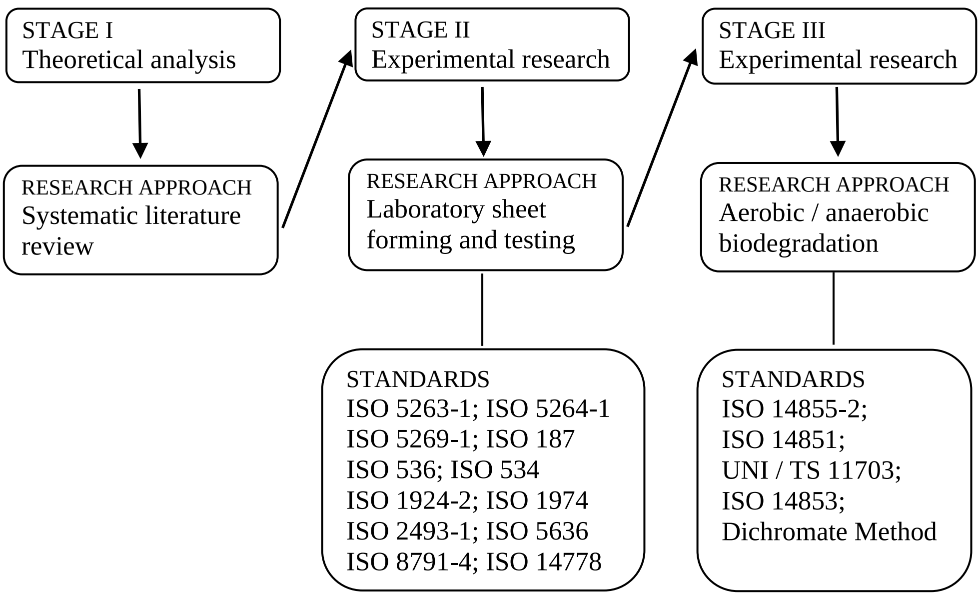


Fig. 4. Methodological research framework flowchart

Experimental stage involved the laboratory-based development of the biodegradable packaging material, its physical-mechanical and barrier properties testing and material’s biodegradability performance under controlled conditions. **Table 6** shows an overview of the key standards utilized at each stage.

Table 6. Experimental research and corresponding standards of performed tests

Stage	**Standard, metdod**	**Description**
Raw materials preparation.	Dry content analysis	Materials moisture analysis using Precisa 310M/HA300.
	ISO 5263-1[147]	Pulps – Laboratory wet disintegration of chemical pulps.
	ISO 5264-1[148]	Pulps – Laboratory beating. Valley beater method.
Paper composite sheet forming – 23 samples.	ISO 5269-1[149]	Pulps – Preparation of laboratory sheets for physical testing. Conventional sheet-former method.
	ISO 187[150]	Paper, board and pulps – Standard atmosphere for conditioning and testing and procedure for monitoring the atmosphere and conditioning of samples.
	ISO 536[151]	Paper and board – Determination of grammage.
	ISO 534[152]	Paper and board – Determination of thickness, density and specific volume.
Paper composite sheet physical-mechanical properties – 20 samples.	ISO 1924-2[153]	Paper and board – Determination of tensile properties.
	ISO 1974[154]	Paper – Determination of tearing resistance – Elmendorf method.
	ISO 2493-1[155]	Paper and board – Determination of bending resistance.
	ISO 5636[156]	Paper and board - Determination of air permeance. Bendtsen method.
	ISO 8791-4[157]	Paper and board – Determination of roughness/smoothness.
	ISO/TS 14778[158]	Paper and board – Measurement of water contact angle by optical methods.
Paper composite sheet biodegradation test – 3 samples.	ISO 14855-2[159]	Determination of the ultimate aerobic biodegradability of plastic materials under controlled composting conditions – Method by analysis of evolved carbon dioxide.
	ISO 14851[160]	Determination of the ultimate aerobic biodegradability of plastic materials in an aqueous medium – Method by measuring the oxygen demand in a closed respirometer.
	UNI/TS 11703[161]	Method for the measurement of the potential production of methane from wet anaerobic digestion.
	ISO 14853[162]	Plastics – Determination of the ultimate anaerobic biodegradation of plastic materials in an aqueous system. Method by measurement of biogas production.
	Chemical Oxygen Demand (COD)[163]	Dichromate Method.

2.2. Raw materials preparation stage

2.2.1. Raw materials

The main raw wood-pulp materials selected for this study were sourced from European manufacturers, ensuring compliance with sustainability standards. Northern bleached softwood kraft (NBSK) pulp, made from pine and spruce, sourced from Billerud (Solna, Sweden). Chemithermomechanical pulp (CTMP), produced from poplar, obtained from Sicem Saga (Reggio Emilia, Italy). Both pulps are certified by the Forest Stewardship Council (FSC) and are suitable for food contact packaging. The physical properties of the pulps, as provided in the manufacturers' technical data sheets, are listed in the following **Table 7**.

Table 7. Physical-mechanical pulps properties

Property	Unit	CTMP	NBSK
Fiber length	mm	1.5	1.9-2.1
Tensile index	Nm/g	min 25	110
Burst index	kPa m²/g	1.2	8.2
Tear index	mN m²/g	6.8	8.5

The paper composite additives, including industrial wheat grain processing by-products — such as wheat, rye, spelt husks, small grains, straw, grass seeds (oats, buckwheat, wild buckwheat), grain dust, and wheat bran (the outer hull of the wheat kernel) — were purchased from Malsena Plius (Vievis, Lithuania).

Dry brewing yeast (*Saccharomyces cerevisiae*) SafAle™ S-33 was procured from Fermentis (Marquette-lez-Lille, France), and dry sugar was obtained from Nordic Sugar (Kėdainiai, Lithuania).

2.2.2. Raw material dry content and agricultural by-products fraction analysis

The dry matter content of the materials was determined using a Precisa 310M/HA300 rapid moisture analyzer. The results of dry content analysis are presented in **Table 8**. The composition of industrial grain processing by-products and wheat bran fractions was determined using 500 µm, 250 µm, 150 µm, and 75 µm sieves (see **Table 9** and **Figure 5**). The different fractions were weighed using laboratory scales with a resolution of 0.01 g. The standard filler composition used in paper production was utilized.

Table 8. Material dry content, %

Material	Dry content %
Northern bleached softwood kraft (NBSK)	93.6
Chemithermomechanical pulp (CTMP)	91.1
Industrial wheat grain processing by-products	87.3
Wheat bran	92.5
Dry brewing yeasts (*Saccharomyces cerevisiae*)	98.8
Dry sugar	99.9

Table 9. Industrial grain processing by-products fraction composition, %

Material	500μm	250μm	150μm	75μm	>75μm
Industrial wheat grain processing by-products fraction, %	43.9	23.9	11.6	12.4	8.3
Wheat bran fraction, %	99.5	0.4	0.1	-	-

Fig. 5. 1-5 sieved industrial wheat grain processing by-products fractions, 6-8 wheat bran fractions

2.2.3. Pulp, agricultural by-products pre-treatment, and yeast cultivation

The pulp disintegration process involved running the pulp at 10,000 revolutions for 5 minutes, adhering to the ISO 5263-1 standard. To prevent alterations in pulp latency, CTMP pulp was soaked in water heated to 40°C for 20 minutes based on producer recommendations. Following this, the pulp underwent a beating process of 10,000 revolutions for 30 minutes, as specified by ISO 5264-1 guidelines.

To simulate the brewing process[164 165], ensure biochemical stabilization, sterilize agricultural by-products, and eliminate bacteria, the grain processing by-products and wheat bran were boiled at 100°C for 10 minutes[166 167]. Dry brewing yeast (*Saccharomyces cerevisiae*) was cultivated in a suspension of highly diluted pulp, sterilized agricultural by-products, and dry sugar at 23°C for 14 hours. The optimal temperature range for SafAle™ S-33 is 18-26°C. The ratio of the dry mass of the pulp-by-products mixture, sugar, and yeast was maintained at 10:2:1[168].

2.3. Paper composite sheet forming and properties testing stage

2.3.1. Sheet forming and drying

23 different compositions (see **Table 10**) of pulp mixtures for paper composite lab sheet formation were prepared, incorporating 15 wt% or 40 wt% agricultural residue filler, with or without added yeast equivalent to 10 wt% of the dry mass of pure pulp and/or the pulp-agricultural residue mix. The preparation of these samples followed the conventional sheet-former method as specified in ISO 5269-1:2005. For laboratory sheet preparation, the final stock (comprising pure pulp and/or pulp

and agricultural residue mixture) was diluted to a consistency between 5 to 2 g/l. Test sheets with a basis weight of 60 g/m² were then formed and dried rapidly. The laboratory sheets were created using a suspension volume that matched the target weight, adhering to the conventional sheet-former procedure.

To assess the potential risk of yeast washout during the standard laboratory sheet-forming process, three additional samples were prepared using a closed-loop sheet-forming method (indicated as "loop", see **Table 10**). In both, the standard and closed-loop methods, process water is discharged from the forming cylinder during the formation of each individual sheet, allowing the pulp composite to settle on the forming mesh and create a sample.

In the standard method, fresh water from the supply system is introduced into the forming cylinder for each new sheet, thereby minimizing the carryover of suspended solids such as nanocellulose or other microparticles between cycles. In contrast, the closed-loop system enables the reuse of the same process water throughout multiple sheet-forming cycles. As a result, suspended microparticles and the yeast-based additive remain in circulation within the system. In each closed-loop cycle, ten sheets were formed. The first three sheets were produced during the system stabilization phase and were excluded from subsequent property analysis to avoid data distortion caused by non-homogeneous particle distribution.

Formed sheets were stacked in a "sandwich structure" between blotting papers (to absorb residual moisture) and pressing plates, and subsequently pressed using an automatic hydraulic press for 4 minutes under 490 kPa pressure. To ensure uniform drying conditions and deactivate yeast in samples with added yeast, all wet-pressed sheets were dried in a drying drum for 90 minutes, with the drum surface reaching a maximum temperature of 78°C.

Table 10. Final material composition and sheet former methods used

Final stock (wood pulp and agricultural by-products ratio)	**Conventional sheet-former method, no added yeast**	**Conventional sheet-former method, 10% added yeast**	**Closed loop sheet-former method, no added yeast**	**Closed loop sheet-former method, 10% added yeast**
NBSK plain	NBSK	NBSK Y	NBSK loop	NBSK Y loop
NBSK with grain by-products 15wt%	NBSK W15	NBSK W15Y	-	-
NBSK with wheat bran 15wt%	NBSK B15	NBSK B15Y	-	NBSK B15Y loop
NBSK with grain by-products 40wt%	NBSK W40	NBSK W40Y	-	-
NBSK with wheat bran 40wt%	NBSK B 40	NBSK B 40Y	-	-
CTMP plain	CTMP	CTMP Y	-	-
CTMP with grain by-products 15wt%	CTMP W15	CTMP W15Y	-	-

CTMP with grain by-products 40wt%	CTMP W40	CTMP W40Y	-	-
CTMP with wheat bran 15wt%	CTMP B15	CTMP B15Y	-	-
CTMP with wheat bran 40wt%	CTMP B40	CTMP B40Y	-	-

2.3.2. Sheet conditioning, trimming and properties testing

Following conditioning based on ISO 187 standards, the drum-dried sheets were cut to a size of 141x141 mm. This was done using a cutting device before assessing their general characteristics, which included basis weight, thickness, and grammage. The grammage of the sheets was measured in line with ISO 536, while the single-sheet thickness was evaluated according to ISO 534. Tensile properties were assessed following ISO 1924, tearing resistance as per ISO 1974, and bending resistance according to ISO 2493-1. Bending stiffness was tested in accordance with ISO 5628.

Furthermore, air permeability and roughness were measured using a Bendtsen tester, following ISO 5636 and ISO 8791, respectively. The determination of bending resistance and stiffness was performed as per ISO 2493-1.

The contact angle measurement was performed according to ISO/TS 14778 to evaluate the wettability of paper sheet samples. A controlled-volume water droplet of 1µl was deposited onto the surface, and its profile was recorded using a high-resolution optical system. Image analysis software determined the contact angle at 0.1 seconds after deposition, capturing the initial liquid-surface interaction. Measurements were conducted across distinct surface regions, including non-particle areas, particle-covered zones, and random locations.

2.4. Paper composite biodegradation testing stage

From the samples tested in the previous research Stage II, the three best-performing sheets (see **Table 11**), selected based on their superior barrier properties, were chosen for biodegradation analysis. These final samples were subjected to both aerobic and anaerobic degradation tests to evaluate their biodegradation efficiency.

Various filler compositions were selected to assess the impact of bran on biodegradation efficiency. To evaluate the effect of yeast, samples with identical bran concentrations, both with and without yeast, were used.

Table 11. Samples selected for biodegradation efficiency testing

Substrate ID	**Bran content (%)**	**Saccharomyces cerevisiae**
NBSK B15	15	No
NBSK B15Y	15	Yes
NBSK B40	40	No
NBSK B40Y	40	Yes

Compost used for aerobic test was taken from a composting plant north of Milan treating selected biowaste and green waste. Anaerobic inoculum was taken from a thermophilic digestor operating at 50 °C in Carimate WWTP (Como, Italy).

2.4.1. Paper composite total solids (TS) and volatile solids (VS) determination

A representative sample of paper composite, sludge, and compost was obtained. The weight of a dry and clean aluminum dish (container) was recorded as (W1). A known quantity of the sample was added to the container and weighed as (W2). The container with the sample was dried in an oven set at 105°C for 24 hours until a constant weight was achieved. The dried container was then removed from the oven and placed in a desiccator to cool to room temperature. The weight of the cooled container with the dried sample was recorded as (W3).

Total Solids (TS) were calculated according to Equation 1:

$$\text{TS}\ (\%) = \left(\frac{W3 - W1}{W2 - W1}\right) \times 100 \qquad (1)$$

The dried samples from the TS determination process were used. The containers with the dried samples (W3) were placed in a muffle furnace set at 550°C and ignited for 2 hours to burn off the volatile solids. (W3) was obtained from the TS determination. After ignition, the containers were removed from the muffle furnace and placed in a desiccator to cool to room temperature. The cooled containers with the non-volatile by-products were weighed and recorded as weight (W4).

Volatile Solids (VS) were calculated according to Equation 2:

$$\text{VS}\ (\%) = \left(\frac{W3 - W4}{W2 - W1}\right) \times 100 \qquad (2)$$

The ratio of VS to TS were calculated according to Equation 3:

$$\text{VS}\ (\%) = \left(\frac{W3 - W4}{W2 - W1}\right) \times 100 \qquad (3)$$

2.4.2. Chemical oxygen demand determination

Chemical Oxygen Demand (COD) was determined using the Dichromate Method. This method aligns with the standard dichromate COD determination method, which involves refluxing the sample with potassium dichromate and sulfuric acid, followed by titration with ferrous ammonium sulfate. This provides a baseline value representing the amount of oxygen needed to chemically oxidize the organic matter present in the sample. The COD values obtained were used as the initial COD in the anaerobic material biodegradation data analysis.

2.5. Aerobic biodegradation test

Compost was sourced from a composting plant located north of Milan, which processes selected biowaste and green waste. The feedstock at this facility is adjusted to an initial carbon-to-nitrogen (C:N) ratio of approximately 25–30:1 to optimize microbial activity and decomposition. Well-aerated compost was prepared and utilized as inoculum in accordance with the guidelines outlined in ISO 14855-2.

This inoculum was then diluted with an inorganic test medium prepared according to ISO 14851:2019. Three types of dry test substrates were cut into 10x10 mm squares and added to the diluted inoculum. The final concentration ratio of total solids in the vessel and the pH adjusted to 7 at the start of the test, as described in ISO 14853. Microcrystalline cellulose served as the reference material. Detailed substrate and inoculum characterization are provided in **Table 12**.

Table 12. Aerobic degradation test materials characterization and mean values

	VS (per unit mass)	**VS/TS**	**Mass, material**	**Mass, VS**	**COD**	**Volume of test medium**	**Working Volume**
Substrate ID	(gVS,S/ kgFM,S)	(%)	(gFM,S /bott)	(gVS,S /bott)	mgO_2 /bott	(mL)	(mL)
B15Y	940.77	99.71	1.0025	0.94	1065.62	200	217
B40	927.09	98.92	1.0049	0.93	1076.95	200	217
B40Y	932.36	99.62	1.0019	0.93	1110.41	200	217
Cellulose	960.71	99.99	1.0027	0.96	1188.20	200	217
Inoculum							
Compost	182.27	38.15	20.00	3.65	-	-	-

For testing, 1110 mL glass vessels were used, with sodium hydroxide in the top cap for CO_2 absorption. To ensure even mixing and temperature homogeneity during BOD testing, the vessels were placed on the IS 12 inductive stirring system. The test vessels were incubated in a temperature-controlled oven, with gentle continuous mixing using a magnetic stirrer. The temperature was maintained at 46°C throughout the entire 30-day incubation period. To prevent oxygen deficiency, air was supplied to the test vessels via an aerator for 5 minutes every 5-6 days.

The selected temperature is within the optimal composting range[169], where both mesophilic and thermophilic bacteria are active[170], promoting microbial activity and pathogen elimination[171 172]. Substrate, blank assays, and positive controls were conducted in triplicates.

The aerobic biodegradability of each test specimen at the end of the test was calculated by obtaining the oxygen pressure values generated from the substrate (hPa/bottle) from the respirometric measuring system controller data. Measurements were taken every 14 days, resulting in a total of 772 measurements over the entire incubation period. This data was transferred to a PC and analyzed. The measured pressure from respirometric methods was converted into the BOD value according to Equation 4:

$$\mathrm{BOD} = \frac{M(\mathrm{O}_2)}{R \cdot T_m} \left(\frac{V_{\mathrm{tot}} - V_I}{V_I}\right) \alpha \left(\frac{T_m}{T_0}\right) \Delta p(\mathrm{O}_2) \qquad (4)$$

where:
$M(O_2)$ = Molecular weight of oxygen (32,000 mg/mol)
R = Gas constant (83.144 L·hPa/(mol·K))
T_0 = Temperature (273.15 K)
Tm = Measuring temperature (319.15 K for performed BOD)
Vtot = Bottle volume [mL]
V1 = Sample volume [mL]
α = Bunsen absorption coefficient (0.03103)
$\Delta p(O_2)$ = Difference of the partial oxygen pressure [hPa]

The test results represent the maximum level of biodegradation determined from the plateau stage of the biodegradation curve. The specific biological oxygen demand of each tested material (BOD_{total}) was calculated as the difference between oxygen consumption in the test flasks and the blanks. Given that the COD of the sample added to each bottle (COD_{sample}) represents the total oxygen demand for the chemical oxidation of the organic matter inserted, the oxygen demand obtained in long duration aerobic biodegradation tests like the ones here perfomed (BOD_{total}), is a close proxy of the biodegradable organic substrate in the bottle ($COD_{sample\ bio}$) and the ratio $BOD_{total}/COD_{samples}$ gives a close proxy of the fraction $COD_{sample\ bio}/COD_{sample}$ and of the biodegradability of the organic compound present.

A more accurate calculation of the CODbio according to the COD mass balance principles, however, should have considered that a part of the $COD_{sample\ bio}$ is converted to bacterial cells by growth (without oxygen consumption) and a fraction if this remains at the end of the test as unbiodegradable cell residuals from bacterial decay. Finally, BODtotal values always slightly underestimate the quantity of biodegradable organics in the sample (CODbio). Formula to calculate CODbio from BODtotal are well described in the literature[173] and were applied here, assuming that 10% of the initial CODbio remained as unbiodegradable organics by-products, according to Equation 5:

$$\text{Biodegradation efficiency (\%)} = \left(\frac{0.9 \times \mathrm{BOD_{total}}}{\mathrm{COD_{sample}}}\right) \times 100 \qquad (5)$$

2.6. Anaerobic biodegradation test

The anaerobic inoculum was left without feeding for 7 days (degassing). Afterwards, according to Italian standard UNI/TS 11703:2018, nutrient media was added, and the inoculum was further diluted. Italian standard UNI/TS11703:2018 was used along with the best BMA test practices.

Three types of dry test substrates, cut into 10x10 mm squares, were then added to the diluted inoculum. Microcrystalline cellulose was used as a reference material. The final concentration ratio of total solids in the vessel and the pH adjusted to 7 at the start of the test were adjusted as described in ISO 14853. Detailed substrate and inoculum characterization are provided in **Table 13**.

Table 13. Anaerobic degradation test materials characterization and mean values

	VS (per unit mass)	**VS/ TS**	**Mass, mat.**	**Mass, VS**	**COD**	**Vol. of tap water**	**Total volume of nu-trients**	**Working Volume**
Substrate ID	(gVS,S/ kgFM,S)	(%)	(gFM, S/bott)	(gVS, S/bott)	mgO_2/ bott	(mL)	(mL)	(mL)
B15Y	940.77	99.71	2.42	2.28	2572.7	74.80	52.8	480.00
B40	927.09	98.92	2.45	2.27	2625.7	74.80	52.8	480.00
B40Y	932.36	99.62	2.44	2.27	2704.3	74.80	52.8	480.00
Cellulose	960.71	99.99	2.39	2.30	2832.2	74.80	52.8	480.00
Inoculum								
Sludge	13.77	57.35	350.00	4.82	-	-	-	-

Biomethane potential (BMP) tests were conducted using a Gas Endeavour III (GE III, BPC Instrument, Sweden) system, which includes 18 units of 500 mL reactors and an equal number of gas flow meters (flow cells) connected to a detection unit for automatic data acquisition. These tests were performed under thermophilic conditions at 55°C[174] [175] [176]. The test vessels were incubated in a temperature-controlled water bath, with gentle and continuous mixing applied to the vessels throughout the entire 30-day incubation period[177] [178]. Substrate, blank assays, and positive controls were conducted in triplicates.

The anaerobic biodegradability of each test specimen was determined by calculating the total cumulative methane values generated from each test (NmL CH_4/bottle). The net methane values were derived by subtracting the methane produced in the blank vessels from the total methane values. These net values were then normalized to the chemical oxygen demand (COD) of the substrate added (NmL CH_4/mg COD) to obtain the final methane production (CH_4 final). Biodegradability was calculated by dividing the normalized methane production by the equivalence factor α (0.32 mL CH_4 produced per mg COD biodegraded)[179].

Biodegradation efficiency was then calculated based on the amount of methane produced compared to the substrate COD added at the beginning of the test, according to the Equation 6:

$$\text{Biodegradation efficiency (\%)} = \left(\frac{\mathrm{CH_4\ Final}}{\mathrm{Theoretical\ CH_4}}\right) \times 100 \qquad (6)$$

3. OUTCOMES OF THE RESEARCH

3.1. Literature review outcomes

The literature review underscores that biodegradable packaging solutions can be optimized to enhance recyclability, minimize resource consumption, and improve environmental efficiency. The strategic selection of renewable raw materials, industrial by-products, and biodegradable coatings ensures that packaging materials remain functional while aligning with circular economy principles. These outcomes directly support the dissertation's objective of creating sustainable, high-performance single-use food packaging that integrates renewable resources while reducing environmental impact.

Raw material savings are achieved by replacing virgin fiber with secondary raw materials and by-products, reducing the demand for primary resources.

Energy consumption reduction is supported by the use of production by-products that do not require additional processing or cultivation, minimizing energy-intensive refining processes.

Improved recyclability is demonstrated by the integration of bio-based single-use packaging into biological recycling cycles, ensuring compatibility with composting and anaerobic digestion systems.

The transition to renewable raw materials is supported as fossil-based components are replaced with bio-based alternatives, lowering environmental impact and reducing dependence on non-renewable sources.

Lower chemical usage is achieved through the incorporation of minimally processed agricultural by-products, eliminating the need for additional chemical treatment and reducing synthetic additives.

Regional industrial symbiosis is promoted by utilizing locally available raw materials and production residues, minimizing transportation emissions and enhancing local resource efficiency.

3.2. Raw materials analysis

Dry content analysis is crucial for maintaining consistency in material composition, as fluctuations in moisture content can lead to inconsistencies in the final product. Additionally, moisture content affects key processing parameters, such as drying times and temperatures, which directly impact production efficiency and material uniformity. Similarly, particle size distribution plays a significant role in determining composite properties. Larger particles can disrupt fiber bonding and affect the paper's mechanical strength, while finer particles may contribute to smoother surfaces and improved filler integration.

Dry industrial wheat grain processing by-products exhibited the highest initial moisture content, nearly 13% and displayed a wider particle fraction distribution compared to wheat bran. The highest proportion of industrial wheat grain processing by-products comprised particles larger than 500 µm, with the second-largest share being particles sized between 499-250 µm, accounting for 43.9% and 23.9%, respectively. Conversely, the majority of wheat bran – 99.9% – consisted of particles larger than 500 µm.

3.3. Paper composite sheet forming and properties testing stage

3.3.1. Grammage and thickness

In the subsequent stages, the physical characteristics of the paper, such as grammage and thickness, were evaluated to understand their impact on the paper's performance as packaging material. The combination of grammage and thickness plays a crucial role in determining the overall performance of packaging materials. Higher grammage and appropriate thickness contribute to the strength, durability, and rigidity required for effective packaging. However, the balance between these properties must be carefully managed to avoid issues such as surface damage or excessive rigidity, which could hinder the packaging's flexibility.

Grammage is defined as the mass of paper per unit area, measured in grams per square meter (g/m²). This characteristic impacts the weight and durability of paper packaging. Higher grammage often correlates with stronger, more durable paper. The obtained CTMP samples had a grammage range of 64.6 to 70.1 g/m², while NBSK samples ranged from 64 to 67.3 g/m².

Variations in grammage were attributed to the presence of agricultural by-products and pulp loss during sheet removal and the drying process – notably, cellulose-based blotting papers bonded some agricultural residue particles (refer to **Figure 6** and **Figure 7**).

Due to the protruding surface of these particles, more residue was absorbed onto the blotting paper attached to the non-wire side of the paper sheet.

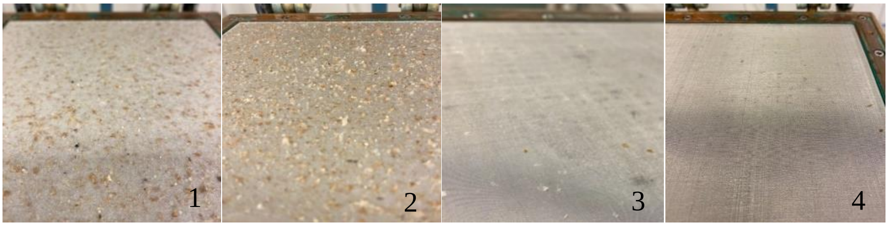


Figure 6. Filler particles during sheet forming and sheet removal: 1, 2 – upper / non-wire paper sheet samples surface before removal from sheet former. 3, 4 – agricultural by-products and pulp leftovers after paper sheet removal

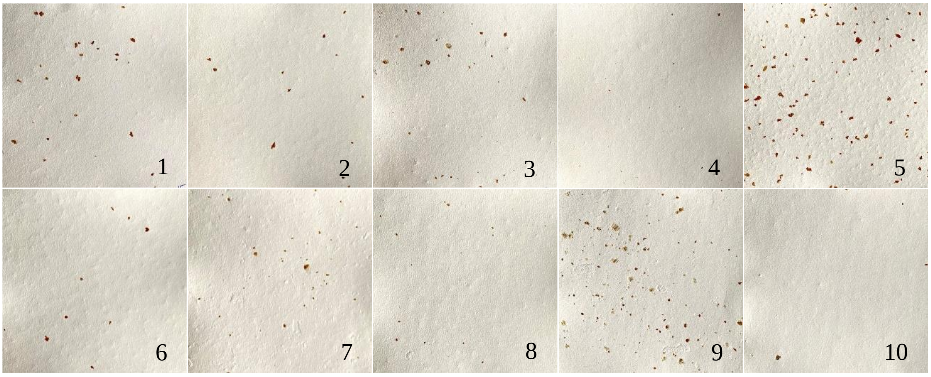


Figure 7. Bloting papers after drying: 1, 2 paper sheet samples filed with 15wt% wheat bran (wire side and non-wire side); 3,4 paper sheet samples filed with 15wt% industrial wheat grain processing by-products (wire side and non-wire side); 5,6 paper sheet samples filed with 40wt% wheat bran (wire side and non-wire side); 7,8 paper sheet samples filed with 40wt% industrial wheat grain processing by-products (wire side and non-wire side); 9,10 CTMP filed with 40wt% industrial wheat grain processing by-products

Thickness affects the rigidity and handling properties of paper packaging. The average thickness of control NBSK pulp was 121 µm, while for CTMP pulp, it was 228 µm. The thickness of filled NBSK samples varied from 117 µm to 202 µm, with the maximum thickness observed in bran-filled paper samples, attributed to the large amount of bran particles (>500 µm).

For CTMP with additives, pulp thickness ranged from 224 µm to 261 µm. Similar to NBSK samples, the maximum thickness was found in bran-filled paper samples. The addition of fillers generally increased the thickness of both CTMP and NBSK papers. CTMP pulp with 40 wt% industrial wheat grain processing by-products was eliminated from further testing due to surface damage during blotting paper removal after the sheet drying process. However, CTMP samples containing 15 wt% industrial wheat grain processing by-products, 15 wt% and 40 wt% wheat bran fillers, as well as NBSK samples incorporating both additives, were subjected to further testing, as the paper sheet surface did not exhibit significant damage.

Fillers like bran and grain by-products have different compositions and particle sizes, which directly influence how they integrate with the pulp fibers. Larger particles, such as those found in bran, tend to increase the overall thickness of the paper because they create more bulk within the sheet structure. These large particles can disrupt the uniform distribution of fibers, leading to an uneven surface and increased variability in thickness. The presence of these larger particles also result in higher grammage, as more material is packed into each unit area of the paper.

The concentration of fillers plays a significant role in determining both grammage and thickness. Higher filler content (e.g., 40 wt%) generally leads to greater variability in these properties. As the filler concentration increases, there is a higher likelihood of uneven distribution within the paper matrix, which can cause localized areas of increased thickness and grammage, especially for fillers like bran, which have larger particle sizes and are more challenging to uniformly distribute.

Fillers interact differently with the pulp fibers, depending on their chemical and physical properties. Some fillers may bond well with the fibers, leading to a more cohesive structure, while others may simply occupy space within the sheet, increasing bulk without significantly contributing to the strength or integrity of the paper. This interaction affects how densely the fibers can pack together, which in turn impacts both grammage and thickness. For example, grain residue fillers tend to integrate more easily with the fibers, resulting in less variability in these properties compared to bran fillers. The summary of paper sheet grammage and thickness results is provided in **Figure 8**.

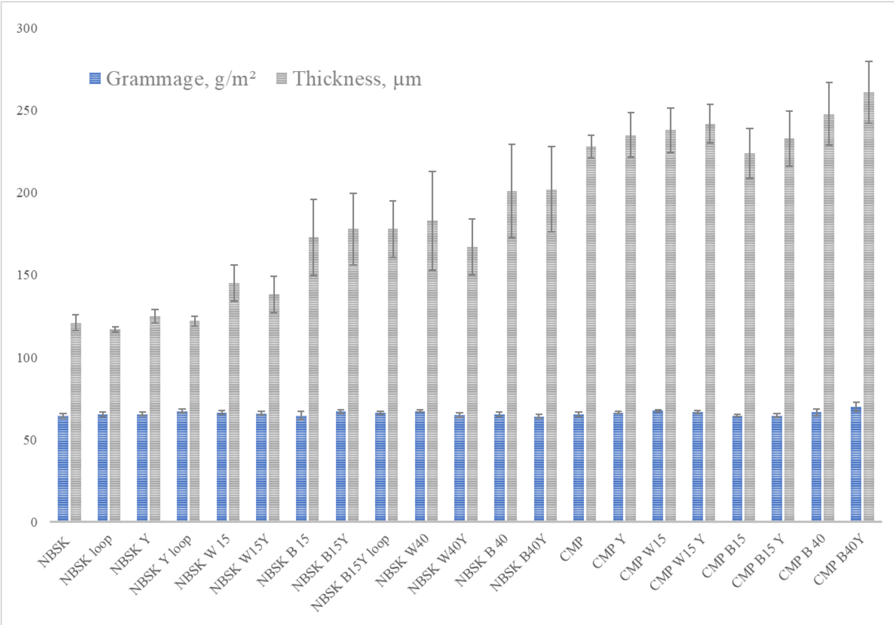


Fig. 8. Laboratory paper sheets grammage and thickness

The findings suggest that while fillers can improve certain aspects of the material's performance, their impact on the manufacturing process and final product quality must be carefully controlled to ensure optimal packaging performance. The inclusion of fillers, especially at higher concentrations, generally increases variability in both grammage and thickness, which could negatively impact the performance of paper packaging in terms of its consistency.

Bran fillers, particularly in larger amounts, contribute to greater variability in both grammage and thickness, which may lead to challenges in maintaining uniformity and quality in the final product. Grain by-products fillers, on the other hand, seem to be more easily integrated, resulting in less variability, especially at lower concentrations.

The increased standard deviation in thickness for samples with higher filler content suggests potential chalanges in achieving consistent mechanical properties, such as rigidity and strength, which are crucial for packaging applications.

3.3.2. Tensile strength

After the determination of grammage and thickness, the experimental research shifted to evaluating the tensile strength of the paper composites, a key indicator of durability and resistance under stress.

Tensile strength is the maximum force that paper can withstand before breaking[180], crucial for the durability and resistance of paper packaging. Plain NBSK laboratory sheets produced in a closed-loop exhibited the best strength properties, followed by those made using the regular sheet forming method. Fines in the closed-loop process enhance strength properties by reducing air permeability and porosity[181 182].

Fillers such as bran and grain by-products can disrupt the fiber-to-fiber bonding within the paper matrix. Tensile strength is largely dependent on the strength and integrity of these bonds, as they hold the paper structure together. When fillers are introduced, especially in larger amounts (e.g., 40 wt%), they can interfere with the close packing of fibers, reducing the number of contact points between fibers and weakening the overall structure.

Same as in grammage and thickness, the size and distribution of filler particles play a crucial role in determining tensile strength. Larger filler particles, such as those found in bran, might create more significant disruptions in the fiber network. These larger particles can interfere with the close interweaving of fibers, resulting in localized weak spots where the fibers are not as closely bonded, leading to a reduction in tensile strength. Additionally, an uneven distribution of fillers throughout the paper matrix can lead to inconsistencies in structural integrity, further compromising its tensile properties.

The interaction between the filler materials and the cellulose matrix also influences tensile strength. Some fillers may not bond well with the cellulose fibers, leading to weak points in the composite structure. For instance, bran fillers, which have a more complex and rigid structure, might not integrate as smoothly with the cellulose matrix, resulting in reduced tensile strength compared to grain residue fillers, which may have better compatibility with the fibers.

Testing results indicated a decrease in tensile strength with increasing filler content. NBSK with 15 wt% industrial wheat grain processing by-products showed a 24% decrease, and 40 wt% same filler reduced tensile strength by 40% from 4.69 kN/m to 2.8 kN/m. Wheat bran decreased tensile strength by 31% (to 3.2 kN/m) with 15 wt% and by 55% (to 2.1 kN/m) with 40 wt% filler.

CTMP sheets exhibited significantly lower tensile properties than NBSK due to shorter fibers[183 184] and higher lignin conten[185]. Plain NBSK had a tensile strength of 4.64 kN/m compared to 1.01 kN/m for CTMP. Agricultural residue fillers generally reduced tensile strength, except for CTMP with yeast, which saw a 10% increase, and CTMP with 15 wt% industrial wheat grain processing by-products, which increased by 8.9%.

Yeast additives in NBSK samples (W15Y, B15Y, W40Y) did not significantly affect tensile strength compared to their non-yeast counterparts. However, NBSK B40Y and plain CTMP Y showed a 10% decrease, while CTMP W15Y and CTMP B15Y showed a 15% increase. All tensile strength testing results are presented in **Figure 9**.

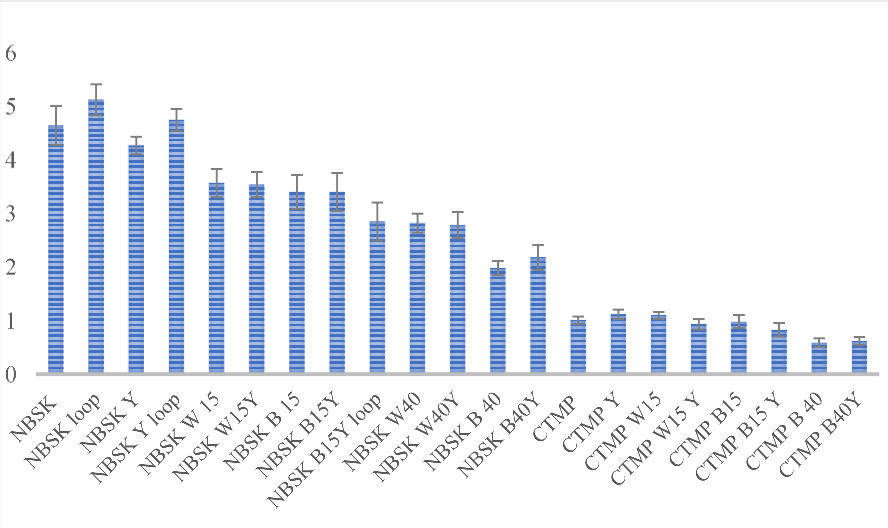


Fig. 9. Laboratory paper sheets tensile strength properties

The addition of fillers, particularly at higher concentrations (40 wt%), generally led to a significant decrease in tensile strength across both NBSK and CMP samples. Bran fillers, in particular, resulted in the most substantial reductions in tensile strength, suggesting that they weaken the composite structure more than grain by-products fillers. Lower filler concentrations (15 wt%) maintained better tensile strength, but the decrease was still noticeable, especially in NBSK samples. The decrease in tensile strength observed with the addition of fillers, particularly at higher concentrations, is primarily attributed to the disruption of fiber bonding, the size and distribution of filler particles, the impact on fiber orientation, the reduction in effective fiber content, and the interaction between the fillers and the cellulose matrix. These factors collectively weaken the paper's structural integrity, making it less able to withstand stress and reducing its overall tensile strength.

Yeast additive had a minimal impact on tensile strength in NBSK samples and generally resulted in a slight decrease in CMP samples. While the yeast improved tensile strength in some cases, such as with 40 wt% bran in NBSK B40Y, the overall effect was either neutral or slightly negative, indicating that the benefits of yeast additives might be more context-dependent and not universally applicable.

While fillers and yeast additives can be used to modify the properties of paper composites, careful consideration must be given to their concentrations and interactions to maintain the desired tensile strength and consistency required for durable and reliable packaging materials.

3.3.3. Strain at break

The next stage of the research explores how different fillers and additives affect the strain at break of the paper composites, providing further insights into their suitability for various packaging applications. Tensile strength and strain at break are complementary properties that together characterize a material's behavior undertension. While tensile strength focuses on the force a material can withstand, strain at break emphasizes how much the material can stretch before it breaks. A material with high tensile strength but low strain at break is strong but brittle – it can resist high forces but breaks quickly without much deformation. In contrast, materials exhibiting lower tensile strength but higher strain at break are more ductile, capable of substantial elongation prior to fracture, yet less resistant to applied loads.

Strain at break measures paper extensibility, a critical property for food packaging applications such as sacks, paper cups, and general packaging. Enhancing fiber-fiber bonding can increase the paper’s extensibility and strength[186]. Strain at break is highly dependent on the continuity and flexibility of the fiber network. When fillers disrupt this network, they can create localized areas where the fibers are not as well bonded and can lead to reduction of material’s ability to elongate under stress and leading to a decrease in strain at break. As filler content increases, particularly with rigid fillers like bran, the paper composite might become more brittle. This brittleness is attributed to the reduced flexibility and increased stiffness that fillers introduce, making the paper less able to stretch before breaking. This effect could be more pronounced at higher filler concentrations, where the filler particles dominate the material’s structure, further reducing its ability to deform under tension.

The results of strain at break testing show that the highest strain at break values was observed in NBSK and NBSK with added yeast in the closed-loop cycle (see **Figure 10**). As NBSK pulp is known for its long, strong fibers, it contributes to the overall flexibility and extensibility of the paper. Longer fibers can form a more interconnected network, allowing the paper to stretch more before breaking. This strong fiber network is a significant factor in achieving higher strain at break values. The closed-loop sheet-forming system likely promotes better retention of fine fibers and fines, which contribute to the paper’s extensibility. In a closed-loop system, the fines that are usually lost in open systems are retained, enhancing fiber-fiber bonding and filling in gaps between longer fibers. This results in a denser, more cohesive fiber network that can elongate more under tension, leading to higher strain at break values. For NBSK samples with industrial wheat grain processing by-products, increasing the filler proportion from 15 wt% to 40 wt% led to an average strain at break decrease of 10%. The use of bran filler resulted in a 20% reduction These decreases, along with higher strain at break values in the closed-loop cycle, can be explained by the higher content of fine cellulose fibers and agricultural particles.

Adding 15 wt% and 40 wt% industrial wheat grain processing by-products to NBSK pulp resulted in approximately a 6% and 16% decrease in strain at break, respectively. Wheat bran filler caused a 26% and 45% decrease in strain at break for

15 wt% and 40 wt% filler levels, respectively. In CTMP pulp, adding 15 wt% industrial wheat grain processing by-products resulted in a 19% lower strain at break, while bran additive led to a 34% decrease. Comparing samples with and without yeast additives, there was no significant impact on NBSK pulp samples, while an approximate 10% decrease was observed in CTMP.

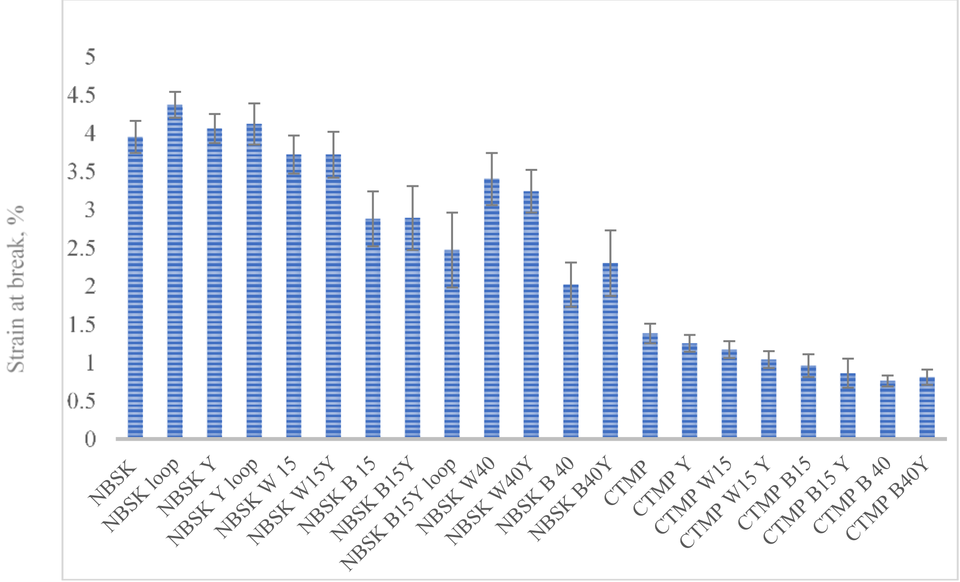


Fig. 10. Laboratory paper sheets strain at break

Grain by-products fillers generally caused a moderate decrease in strain at break, particularly at higher concentrations (40 wt%), but maintained better extensibility compared to bran fillers. These findings indicate that grain by-products serve as a more appropriate filler when flexibility retention is a priority. Bran fillers significantly reduced the strain at break, especially at higher concentrations, making the paper more brittle and less suitable for applications requiring flexibility.

Yeast additives had a mixed impact on strain at break. The highest strain at break values in NBSK and NBSK with added yeast in the closed-loop cycle were achieved primarily due to the superior fiber quality of NBSK, the retention and integration of fines in the closed-loop system, enhanced fiber-fiber bonding, and the potential flexibility-enhancing effects of the yeast additive. In samples with bran fillers, yeast showed a minimal or slightly positive effect, suggesting some potential for improving flexibility. However, in CTMP samples, yeast generally led to a further reduction in strain at break, indicating a potentially negative impact on extensibility in these cases.

The standard deviation data indicates that higher filler content, particularly bran, increases variability in strain at break, which could lead to inconsistent performance in practical applications.

Overall, the results emphasize the need to carefully balance filler type and content to optimize both the tensile properties and strain at break, ensuring that the paper composites meet the specific requirements of their intended packaging applications.

3.3.4. Tear resistance

The ideal material for applications like packaging often requires a balance between tensile strength, strain at break, and tear resistance. Materials that are strong, can stretch sufficiently before breaking, and resist tearing provide the best overall performance in protecting contents and maintaining integrity under stress. An increased strain at break generally contributes to improved tear resistance, as materials that undergo greater elongation prior to failure are more effective in absorbing and dissipating the mechanical energy associated with tearing. If a material can elongate significantly, it is more likely to resist the progression of a tear.

Tear resistance depends on the degree of fiber refinement, fiber adhesion, fiber strength, fiber length, and quality[187] and continuity of the fiber network within the paper. When fillers, particularly those with larger particles like bran, are introduced, they can disrupt this network by creating gaps or weak spots between fibers. This disruption can reduce the paper's ability to resist tearing, as the fibers become less interconnected and thus less capable of distributing and absorbing the energy of a tear. Higher concentrations of fillers can further reduce tear resistance by introducing more substantial disruptions into the fiber network, leading to a greater likelihood of tearing under stress.

Testing revealed that tear strength generally decreased with the increase of both industrial wheat grain processing by-products and wheat bran fillers. The lowest tear resistance was observed in samples with bran filler. Adding 40 wt% bran filler in both NBSK and CTMP pulps reduced tear resistance by approximately 30%. For 15 wt% bran additives, tear resistance decreased by 14%, from 839 mN to 737 mN in NBSK, and by 29% to 592 mN in CTMP pulp samples.

Industrial wheat grain processing by-products had a lower impact on tear resistance. There was no significant difference in tear resistance with 15 wt% additive in either NBSK or CTMP pulp, but a 40 wt% filler in NBSK resulted in an 18.8% decrease in tear resistance.

Comparing samples with and without yeast additives, there was an average decrease of 7% in tear resistance in samples with yeast, except for plain NBSK and NBSK with 15 wt% bran filler, which showed an average increase of 4%.

All tear resistance testing results are shown in **Figure 11**.

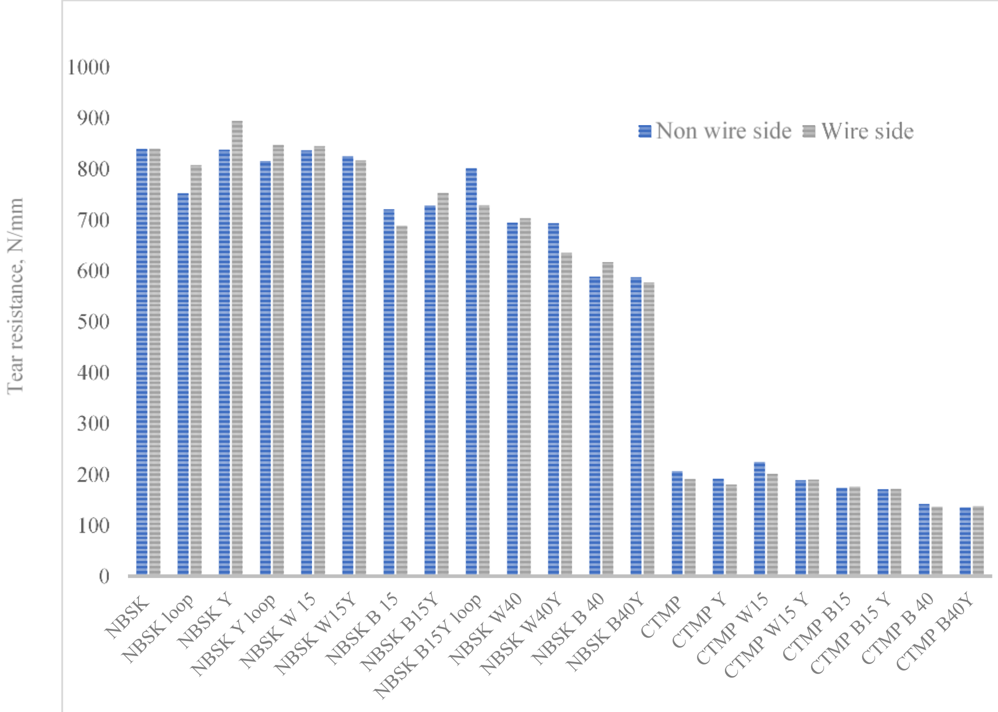


Fig. 11. Laboratory paper sheets tear resistance testing results

The results show that both grain by-products and wheat and bran fillers negatively impacted tear resistance, with bran showing a more pronounced effect. The impact was more severe at higher filler concentrations, where tear resistance decreased significantly.

Similar to NBSK, bran fillers had a more negative impact on tear resistance than grain by-products fillers in CMP samples. High concentrations of bran led to the most significant reduction in tear resistance, confirming the detrimental effect of high filler content on this property.

Yeast additives generally had a minimal impact on tear resistance in both pulp samples. In some cases, such as NBSK Y, there was a slight improvement, but in other cases, particularly with higher filler content, yeast additives exacerbated the reduction in tear resistance.

Overall, the results indicate that while fillers can modify the tear resistance of paper composites, the type and concentration of fillers are crucial in determining the extent of their impact. The impact of fillers on tear resistance is primarily attributed to the disruption of the fiber network, reduction in fiber-fiber bonding, and the size and distribution of the filler particles. Higher filler concentrations, especially with bran, lead to significant reductions in tear resistance, making the paper more prone to tearing.

Yeast additives appear to have limited effectiveness in improving tear resistance, particularly at higher filler concentrations. This information is valuable for optimizing the composition of paper composites to achieve the desired balance of mechanical properties for specific packaging applications.

3.3.5. Bending stiffnes

Bending stiffness measures the rigidity[188] of paper and its resistance to bending, influenced by the modulus of elasticity and thickness. This property is crucial for the physical protection provided by packaging[189] and is affected by paper thickness and grammage[190]. It measures the rigidity of paper and its resistance to bending, which is directly influenced by the material's modulus of elasticity and thickness. The property is closely related to the other key mechanical attributes, such as tensile strength, strain at break, and tear resistance, all of which contribute to the overall durability and performance of packaging materials. Bending resistance is the force needed to bend a paperboard sample through 15°, while bending stiffness is measured at a 5° deflection[191 192].

Bending stiffness is heavily reliant on the integrity and continuity of the fiber network within the paper. The addition of fillers reduces the proportion of fibers in the paper composite; since fibers play a critical role in contributing to bending stiffness, a decrease in fiber content can compromise the structural integrity of the paper. Fillers, particularly in higher amounts, can affect bending stiffness properties by creating a more heterogeneous structure that may not distribute stress evenly across the material. This can reduce the paper's ability to resist bending, as the structure becomes less uniform and more prone to deformation.

As the test results illustrate, the highest bending stiffness values were found in the CTMP samples, attributed to their greater thickness. NBSK samples exhibited thicknesses ranging from 117 µm to 202 µm, while CTMP samples ranged from 224 µm to 261 µm. Fillers generally decreased bending stiffness. In CTMP pulp, 15 wt% industrial wheat grain processing by-products caused a minimal 1.3% decrease. However, 15 wt% and 40 wt% bran fillers reduced stiffness by 21.3% and 44.5%, respectively. In case of NBSK pulp, 15 wt% and 40 wt% industrial wheat grain processing by-products reduced stiffness by 9.1% and 29%, while bran fillers caused decreases of 21.4% and 43.9%.

The addition of yeast further reduced bending stiffness, indicating decreased resistance to folding or bending and, consequently, decreased paper rigidity. The results of the bending stiffness tests are presented in **Figure 12**.

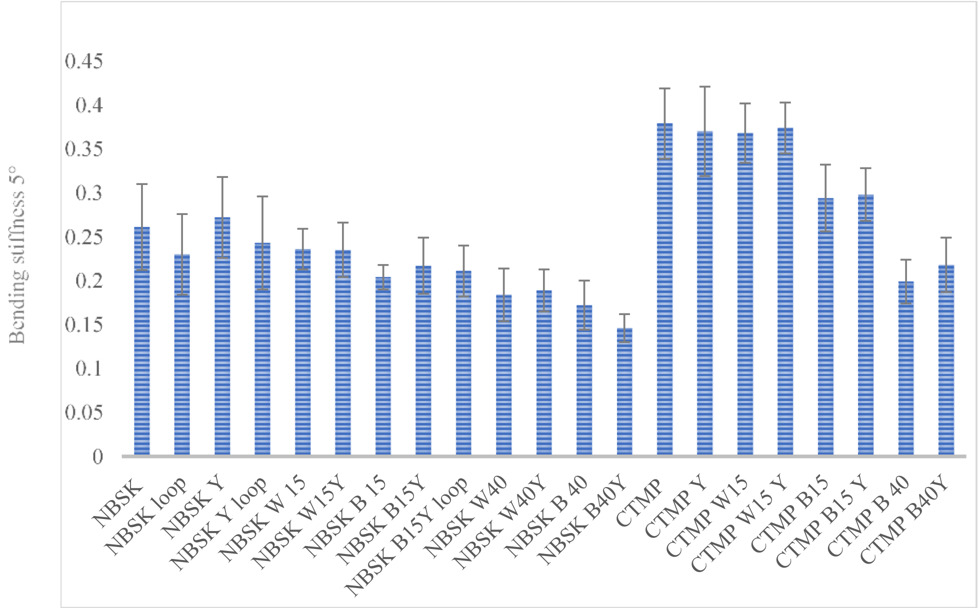


Fig. 12. Laboratory paper sheets stiffness

The analysis revealed that, consistent with previously tested properties, fillers—particularly bran—significantly reduce bending stiffness. Higher filler content leads to greater losses in rigidity by disrupting the fiber network, decreasing the effective fiber content, and compromising the uniformity of the material's structure.Yeast additives exhibited a mixed impact: while they generally reduced bending stiffness when combined with fillers, they slightly increased stiffness when used alone in NBSK samples. This indicates that while fillers tend to compromise the structural integrity of the material, the effect of yeast can vary depending on its interaction with other components in the composite.

3.3.6. Roughness

As previously noted, in the development of paper composites for packaging applications, understanding and optimizing material properties such as tensile strength, strain at break, tear resistance, and bending stiffness are crucial for ensuring the durability, rigidity, and overall performance of the packaging material. These properties directly influence the ability of the material to protect its contents, withstand handling stresses, and maintain structural integrity. However, another critical aspect of packaging performance is surface roughness, particularly for coated or barrier packaging applications.

Surface roughness affects the effectiveness and choice of coating technologies[193], which are essential for enhancing the material's barrier properties against moisture, gases, and other environmental factors. A smoother surface facilitates better coating adhesion and uniformity, which in turn can improve the protective qualities of the packaging. As such, optimizing surface roughness is key to achieving a high-performance packaging material that meets the diverse demands of modern packaging requirements. Roughness is measured by the air volume (ml/min) leaking between a probe and the surface, with lower values indicating smoother surfaces.

The interaction between fillers and the cellulose fiber matrix can influence surface roughness. Fillers that do not bond well with the fibers or that have a different surface texture can create a rougher surface. For example, bran fillers may not integrate as smoothly with the cellulose fibers, leading to more pronounced surface irregularities. As surface roughness is also influenced by how well the filler particles adhere to the fiber matrix, poor adhesion can lead to loose particles on the surface, which contribute to roughness. In contrast, good adhesion, possibly enhanced by yeast additives, can help create a smoother surface by ensuring that the fillers are more evenly distributed and bonded to the fibers.

As with other properties such as tensile strength, strain at break, tear resistance, and bending stiffness, the size and distribution of filler particles play a significant role in determining the surface roughness of paper composites. Larger particles or unevenly distributed fillers can cause more substantial disruptions on the paper’s surface, leading to increased roughness. For instance, bran fillers, which have larger particle sizes compared to grain by-products, are more likely to raise surface roughness due to their more pronounced presence on the paper’s surface.

During the performed material testings, the lowest initial surface roughness was observed in plain NBSK pulp with yeast additive produced in a closed loop. Compared to standard methods, a 12% smoother surface was achieved with yeast in a closed loop. NBSK sheets with 15 wt% bran showed slightly improved smoothness, while no significant difference was noted with standard methods. Adding yeast resulted in a 25% smoother surface in NBSK with industrial wheat grain processing by-products. Other samples showed no significant difference, suggesting that higher yeast and small particle concentrations might enhance surface smoothness.

In general, the incorporation of agricultural fillers increased the surface roughness of the paper. However, samples containing industrial wheat grain processing by-products exhibited smoother surfaces, likely due to the smaller particle size of the filler. Higher roughness was observed on the non-wire side due to protruding agricultural particles (see **Figure 6**, samples 1 and 2).

In NBSK pulp, adding 15 wt% industrial wheat grain processing by-products and bran increased roughness by 69% and 116%, respectively. With 40 wt% fillers, roughness increased by 135% and 159%, respectively. In CTMP pulp, fillers typically increased smoothness except for 40 wt% bran, which had no significant effect. Adding 15 wt% agricultural fillers resulted in a 20% smoother surface with industrial wheat grain processing by-products and 19% smoother with bran. Complete roughness test results are in **Figure 13**.

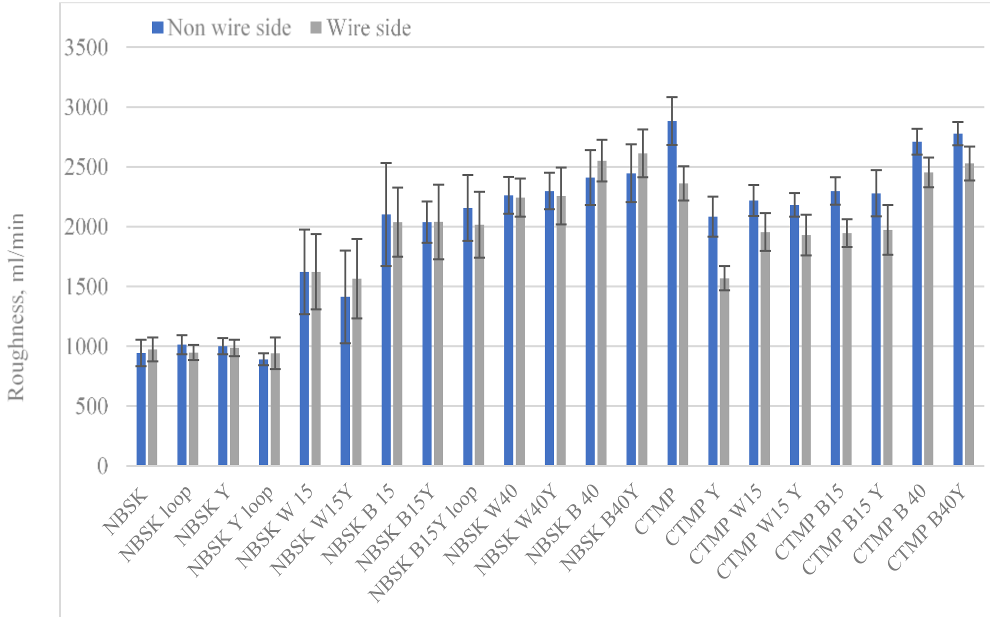


Fig. 13. Laboratory paper sheets roughness testing results

The overall impact of fillers and yeast additives on the material properties of paper composites is complex and multifaceted. Fillers, particularly bran, tend to negatively affect key properties such as bending stiffness and surface roughness, with higher filler content leading to more pronounced losses in rigidity and increased surface irregularities. On the other hand, yeast additives exhibited a mixed impact, generally improving surface smoothness when used alone or in combination with certain fillers, but reducing bending stiffness in combination with others.

The findings indicate that, although fillers can be effective in modifying the mechanical properties of paper composites, their use must be carefully optimized to avoid compromising essential properties such as stiffness and surface smoothness.

Yeast additives, meanwhile, offer potential benefits in enhancing surface smoothness, which is crucial for coated and barrier packaging applications, but their overall impact needs to be evaluated in the context of the specific fillers and processes used. Optimizing the combination of these components is key to developing high-performance paper composites that meet the diverse requirements of modern packaging applications.

The testing and analysis of paper composite properties reveal that the use of fillers and yeast additives can significantly influence the material's mechanical and surface characteristics. While fillers like bran and industrial wheat grain processing by-products can be used to modify the properties of paper composites, their concentration and interaction must be carefully managed to avoid compromising key properties such as tensile strength, strain at break, tear resistance, and bending stiffness.

Yeast additives offer mixed benefits, sometimes improving surface smoothness and slightly enhancing flexibility, but they may also reduce other properties such as bending stiffness, depending on the filler combination. The findings suggest that the development of high-performance paper composites for packaging requires a nuanced approach that carefully balances the type and concentration of fillers and additives to meet the specific demands of the intended application.

Ultimately, the successful optimization of these components will enable the production of paper composites that meet the functional packaging requirements.

3.3.7. Barrier properties: air permeance

The comprehensive analysis of paper composite physical-mechanical properties revealed the complex interplay between fillers, yeast additives, and the resulting mechanical and surface characteristics of the material. Each property – grammage, thickness, tensile strength, strain at break, tear resistance, bending stiffness, and surface roughness – plays a role in determining the overall performance and suitability of paper composites for packaging applications.

In addition to these mechanical properties, the barrier properties of the paper are equally important for packaging applications. Effective barrier properties ensure that the packaging can protect its contents from external elements such as moisture, gases, and contaminants. The surface roughness of the paper is particularly relevant to barrier properties, as it affects the adhesion and uniformity of coatings applied to enhance these barriers. A smoother surface allows for better coating application, which in turn improves the paper's resistance to moisture and gases, enhancing its protective capabilities. However, to fully assess and optimize the barrier properties, it is also essential to evaluate air permeability and the material's hydrophobicity. These factors contribute to the paper's ability to resist moisture penetration and control the passage of air, both of which are critical for maintaining the integrity of the packaging and its contents over time.

Air permeance measures the average volume of air passing through the material per minute at elevated pressure[194]. Because of the hydrophilicity and porosity of cellulose fibers, paper and cellulose-based packaging exhibit weak barrier properties like oxygen and water vapor permeability[195]. Air permeance is a crucial factor in determining the barrier properties of paper and cellulose-based packaging materials. It measures the ability of air to pass through the material, which is directly related to its effectiveness in preventing the penetration of gases like oxygen, a critical consideration for packaging sensitive products.

Fillers, especially those with larger or irregularly shaped particles, might increase the overall porosity of the paper composite. As these particles are introduced into the fiber matrix, they create more voids and gaps between the fibers, which allows air to pass through more easily. This increased porosity is a primary reason for the higher air permeance, as it weakens the material's ability to block the passage of air and gases. Higher concentrations of fillers generally exacerbate the issues of increased porosity and disrupted fiber bonding. As more fillers are incorporated into the paper, the fiber network becomes increasingly interrupted, leading to a less uniform and more porous structure. Additionally, uneven distribution of fillers can create localized areas with higher permeability, further compromising the barrier properties of the paper. As a result, all CTMP and NBSK samples with agricultural by-products exceeded 3000 ml/min air permeance and are not shown in **Figure 14**.

The lowest initial air permeance was observed in plain NBSK pulp made in a closed loop, which showed a 45% higher air permeance compared to the standard sheet-making method. Adding yeast increased air permeance from 1752 ml/min to 3561 ml/min (50.8%) in CTMP and from 2440 ml/min to 3216 ml/min (24%) in NBSK. Yeast-added samples with agricultural fillers showed no significant difference, as all samples exceeded 3000 ml/min.

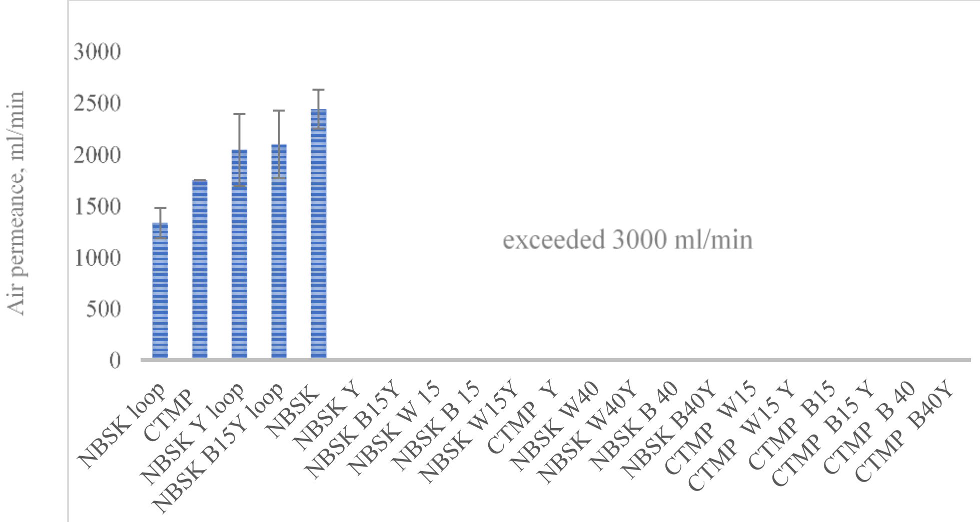


Fig. 14. Laboratory paper sheets air permeance

The findings highlight the significant impact that fillers and yeast additives have on the air permeance of paper composites. While the closed-loop process offers some improvement in reducing air permeance by enhancing fiber bonding, the introduction of fillers dramatically increases the material's porosity, severely compromising its barrier properties. Yeast additives further exacerbate this issue by increasing air permeance, both in standard and closed-loop processes, making the paper less effective as a barrier material.

For applications where air and gas permeability are critical, the use of fillers and yeast must be carefully controlled. Alternatives or additional treatments may be necessary to achieve the required barrier properties.

3.3.8. Barrier properties: water contact angle

Hydrophobicity, or the ability of a material to repel water, is another critical aspect of barrier properties in paper composites used for packaging. The degree of hydrophobicity is typically measured by the contact angle, which reflects how a liquid interacts with the surface of the material. A higher contact angle indicates greater hydrophobicity, meaning the surface resists wetting and is less likely to absorb moisture – a contact angle of 0° indicates complete wetting, 0°-90° indicates wettable, and above 90° indicates not wettable.

This property is crucial for packaging applications where protection from water and other liquids is essential to maintain the integrity and quality of the packaged goods. Contact angle (wetting angle) measures the wettability of cellulose-based material by a liquid, with values indicating how a liquid spreads on or is absorbed by the surface[196].

The inclusion of fillers and additives significantly influences the hydrophobicity of paper composites. Fillers such as bran and industrial wheat grain by-products introduce variations in surface texture and composition, which can either enhance or diminish the material's ability to repel water, depending on their concentration and distribution. For instance, a rougher surface created by these fillers tends to trap air pockets beneath water droplets, reducing the actual contact area between the water and the paper surface. This heterogeneous surface disrupts the smoothness of the cellulose fibers, making the surface less conducive to water absorption.

Yeast additives, on the other hand, interact with cellulose fibers in complex ways that can alter the surface characteristics of the paper, thereby affecting its wettability. The method of production, whether standard or closed-loop, also plays a crucial role in how fillers and additives affect the contact angle. The closed-loop process, which retains more fines and promotes better integration of fillers into the fiber matrix, can enhance the uniformity and smoothness of the surface, leading to higher contact angles and improved hydrophobicity.

In the performed testing the highest average contact angle value (measured on the inner and outer sides; measured in the area without filler, filler area, and random area) was obtained in the CTMP B15Y sample and reached 73°, followed by the CTMP sample with 40 wt% bran filler, which had a contact angle of 71°. Measuring individual zones of paper composite samples, the highest value was observed in the filler area on the inner side of the CTMP B15Y sample, reaching 90° – the water drop did not penetrate through the large bran fraction.

Significant differences in contact angle between the inner and outer sides of the samples were observed only in NBSK samples without fillers – the inner side is more hydrophobic due to contact with the mesh and the deposition of the finest cellulose particles on the bottom side. For these reasons, higher contact angle values were recorded in random area measurements on the inner side of the samples.

The effect of the yeast additive varies depending on the sheet production method. The most significant change in contact angle was observed in NBSK pulp without fillers when producing samples using the closed-loop method – in the sample without yeast, the contact angle value was only 22°, while adding yeast increased the contact angle to 72°. In similar samples produced using the standard method, the yeast additive reduced hydrophobicity from 33° to 21°. This indicates that yeast interacts with fine cellulose fibers, thereby increasing hydrophobicity.

Figures 15 and **16** show contact angle results for non-wire and wire sides, respectively.

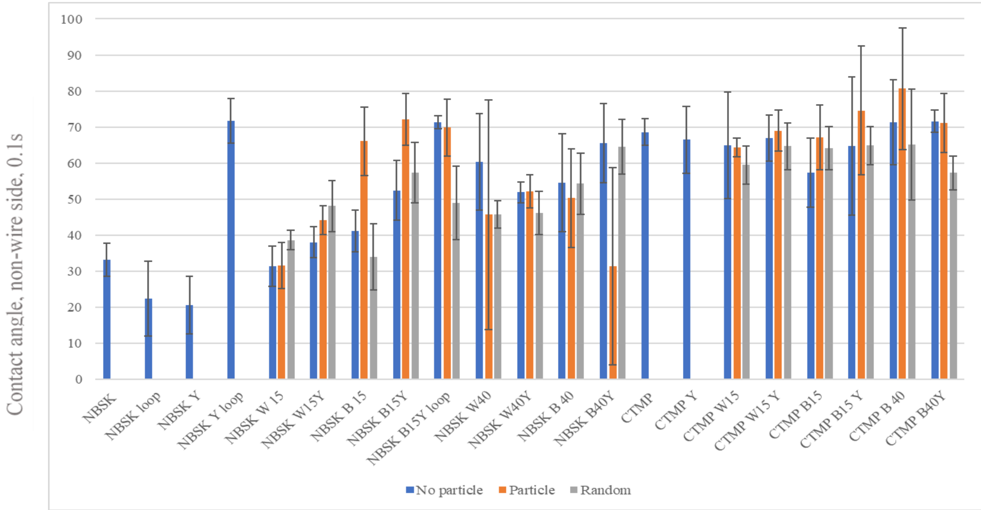


Fig. 15. Paper sheets contact angle testing results of non-wire side, 0.1s

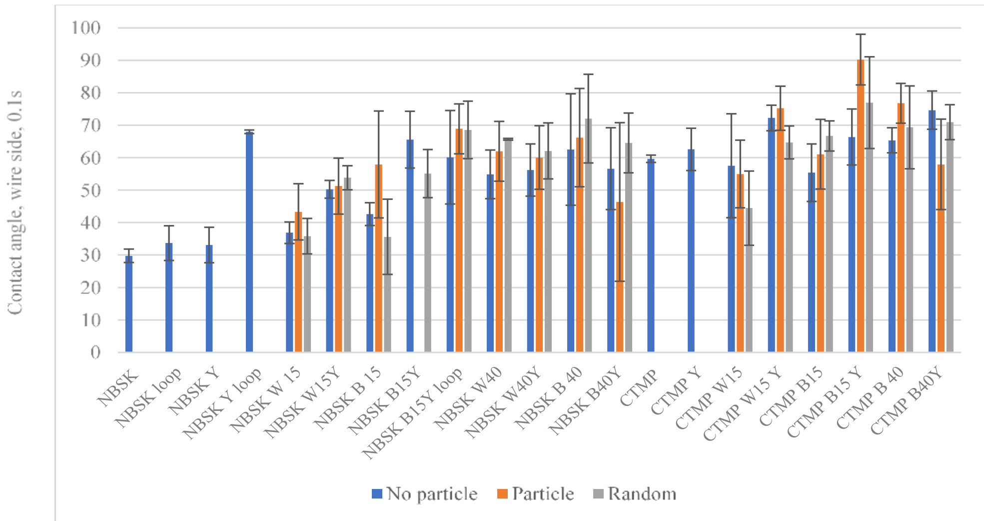


Fig. 16. Contact angle testing results of wire side, 0.1s

The results of the contact angle indicate, that in CTMP samples, the presence of bran fillers and yeast additives generally increased the contact angle, indicating improved hydrophobicity. In contrast, NBSK samples showed more varied responses, with significant differences depending on the production method (standard vs. closed-loop) and the presence of yeast.

The introduction of fillers, particularly bran, increases the surface roughness of the paper composite. Rough surfaces can trap air pockets under the water droplet, reducing the contact area and leading to a higher contact angle. Bran fillers, especially at higher concentrations, create a heterogeneous surface with large particles that disrupt the uniformity of the cellulose fibers. This disruption can reduce the material's ability to absorb water, resulting in higher contact angle values.

3.3.9. Properties summary and comparison of lab-made materials with market examples

The overall summary of the paper composite average values from laboratory sheet testing is presented in **Table 14**. This table provides a comprehensive comparison of all samples, including control and modified paper composites, with respect to their general characteristics, physical-mechanical properties, and barrier properties.

To facilitate a clear understanding of how each modification – such as the addition of bran or wheat fillers and yeast additives – affected the material properties, color coding has been applied to the data: green indicates an increase in the property value compared to the control, while red indicates a decrease. This visual aid helps to quickly identify trends and the impact of different modifications on the overall performance of the paper composites.

Table 14. Second research stage testing result summary

Sample	General characteristics		Physical-mechanical properties				Barrier properties	
	Gramm-age, g/m²	Thick-ness, μm	Tensile stren-gth, kN/m	Strain at break, %	Tear resist-ance, mN	Ben-ding, mN	Air perm., μm/ Pa-s	Con-tact angle, °
CTMP (control)	65.33	228	1.01	1.38	199	96.30	1752	64.10
CTMP B15	64.63	224	0.99	0.96	175	76.50	exceed.	61.94
CTMP B15Y	64.58	233	0.83	0.86	172	75.10	exceed.	72.94
CTMP B40	66.50	248	0.59	0.76	140	51.10	exceed.	71.42
CTMP B40Y	70.05	261	0.62	0.81	137	55.70	exceed.	67.25
CTMP W15	67.42	238	1.10	1.17	213	94.70	exceed.	57.62
CTMP W15Y	66.88	242	0.94	1.04	189	95.20	exceed.	68.80
CTMP Y	66.38	235	1.12	1.25	186	95.30	exceed.	64.53
NBSK (control)	64.30	121	4.64	3.95	839	70.60	2441	31.50
NBSK	64.58	173	3.40	2.88	705	53.10	exceed.	46.20

B15								
NBSK B15Y	67.05	178	3.40	2.89	740	57.80	exceed.	50.45
NBSK B15Y loop	66.30	178	2.85	2.47	765	55.10	2100	64.63
NBSK B40	65.33	201	1.98	2.02	603	41.80	exceed.	59.99
NBSK B40Y	64.10	202	2.18	2.30	582	37.30	exceed.	54.85
NBSK loop	65.40	117	5.12	4.37	780	65.00	1334	28.04
NBSK W15	66.35	145	3.57	3.72	841	64.20	exceed.	36.30
NBSK W15Y	66.00	138	3.54	3.72	821	63.00	exceed.	47.61
NBSK W40	67.32	183	2.82	3.40	699	51.30	exceed.	55.74
NBSK W40Y	64.88	167	2.78	3.24	664	48.70	exceed.	54.76
NBSK Y	65.50	125	4.27	4.06	866	75.70	exceed.	26.83
NBSK Y loop	67.30	122	4.74	4.12	830	66.90	2046	69.85
Fast food packaging examples	75–325	100–650	MD: 7.9–15.6 CD: 4.5–8.5	NA	MD: 950–1830 CD: 1000–2100	MD: 125–415 CD: 65–250	NA	74.2–82.7

Fast-food packaging generally does not require high levels of tensile strength, strain at break, or tear resistance, as these materials are intended for short-term use and are not subjected to prolonged mechanical stresses. The primary function of such packaging is to provide adequate barrier properties, sufficient stiffness for handling, and ease of disposability. The physical-mechanical properties observed in the lab-made composites, if produced on an industrial scale, would likely meet the necessary requirements for their intended purpose due to the following factors:

Increased grammage. The grammage used in the lab-made composites was based on laboratory sheet-making standards (target basis weight of 60 g/m²), which set a benchmark for experimental consistency rather than application-specific optimization. Consequently, it cannot be directly compared to industrial materials, where grammage is tailored to meet specific functional requirements, such as durability or stiffness. In general, higher grammage typically results in greater fiber density, which enhances tensile strength as fibers form more bonds. Materials with higher grammage often exhibit increased elasticity, as additional fibers can absorb stress before breaking. Additional fibers in higher grammage sheets improve tear resistance, particularly in the cross direction (CD).

Fiber alignmen. Industrial processes align fibers in the machine direction (MD) and cross direction (CD), optimizing strength along specific axes. Controlled fiber orientation and bonding improve the material's ability to distribute stress, increasing flexibility and strain at break. Lab-made sheets typically exhibit a random, isotropic fiber arrangement due to the manual or semi-manual sheet formation process. The absence of MD/CD alignment means the material does not exhibit direction-specific strength advantages. Instead, the tensile strength, strain at break, and tear resistance are uniform in all directions but generally weaker than industrially produced sheets with optimized alignment.

Industrial processing techniques. Industrial pressing increase fiber packing density, enhancing both tensile strength and stiffness while maintaining thinner profiles. These techniques ensure a more uniform material structure, reducing variability and improving performance under mechanical stresses. Random fiber orientation limits the sheet's ability to efficiently distribute stress, reducing flexibility and resistance to mechanical forces. This leads to lower strain at break and lower tear resistance compared to industrial sheets.

Decreased air permeance, while indicating lower oxygen barrier properties, is not a significant concern for fast food packaging. These products are consumed quickly and do not require long-term preservation, so the ability to block oxygen or other gases is less critical. What is crucial, however, is the material's ability to resist moisture and grease, which is where the increased hydrophobicity of the composites becomes particularly valuable. Fast food items often contain liquid components such as salad dressings, sauces, or toppings, making it essential for the packaging to prevent seepage and maintain structural integrity despite exposure to these substances.

The enhanced hydrophobicity, as indicated by the higher water contact angle values in the paper composites with fillers, ensures that the packaging can effectively repel liquids, preventing them from soaking through and compromising the packaging. This property is vital for maintaining the cleanliness, safety, and convenience of the packaging, ensuring that it performs its role effectively during the brief period it is needed. Therefore, even with the reduction in some physical-mechanical properties, the improved hydrophobicity and the alignment of air permeance with the requirements for fast food packaging make these paper composites well-suited for their intended use.

Therefore, based on the results, paper composites with bran fillers were selected for the next experimental research stage – biodegradation. The selected materials, chosen for their superior hydrophobic properties, are as follows:

CTMP B15Y (72.9°): This sample exhibited the highest average contact angle among all the samples tested. The combination of 15 wt% bran filler with yeast additive likely contributed to a more hydrophobic surface. The large bran fractions in the filler area, particularly on the inner side of the paper, could have created a more pronounced surface texture, resulting in reduced wettability. The yeast additive might have further enhanced this effect by interacting with the cellulose fibers and creating a less absorbent, more water-resistant surface.

CTMP B40 (71.4°): This sample, containing 40 wt% bran filler, also showed a high contact angle value. The increased concentration of bran filler likely contributed to the surface roughness and heterogeneity, leading to less water penetration and a higher contact angle. The larger particles of bran filler may have created a more textured surface, which can trap air and reduce the actual contact area of water, resulting in greater hydrophobicity.

Figure 17 provides a comprehensive visualization of how wheat bran and grain by-product fillers influence key paper properties, revealing interdependencies between grammage, thickness, tensile strength, tear resistance, bending stiffness, and contact angle. The main factor affecting these properties is the type and concentration of fillersand pulp type. Higher filler content generally increases grammage and thickness but decreases tensile strength, tear resistance, and bending stiffness, while improving hydrophobicity.

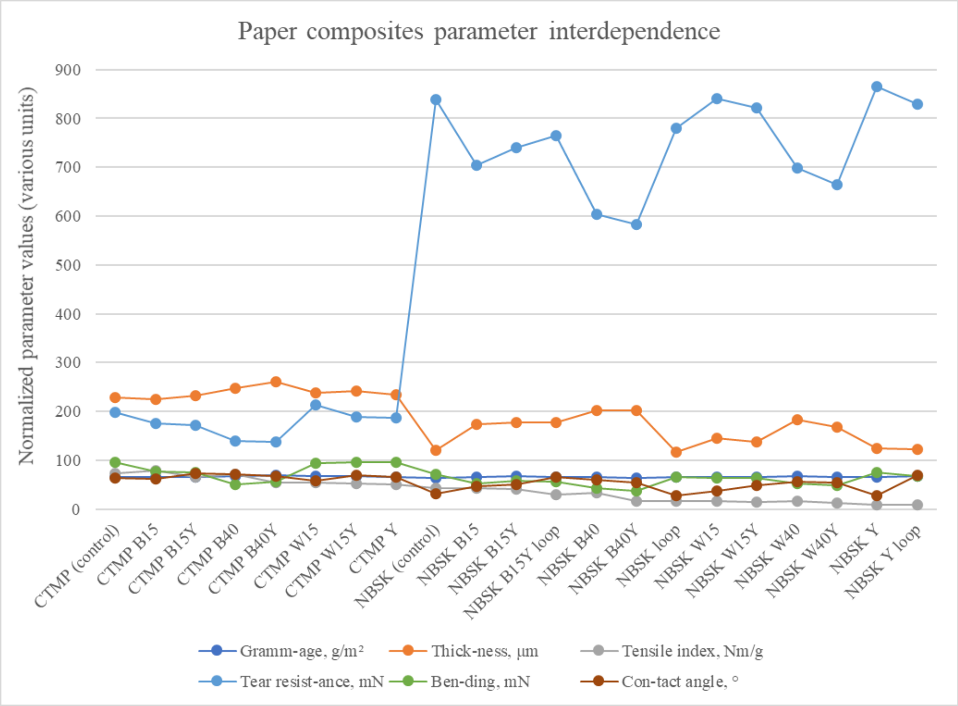


Fig. 17. Paper composites parameter interdependence

A positive interconnection exists between grammage and thickness, as higher filler content results in bulkier and heavier paper sheets. This is evident in CTMP B40Y (70.05 g/m², 261 µm), which has a significantly higher grammage and thickness than the control (65.33 g/m², 228 µm). A similar trend is observed in NBSK samples, where NBSK B40 (65.33 g/m², 201 µm) has greater bulk than the control (64.3 g/m², 121 µm).

While thickness normally shows a positive interdependence with strength, the presence of fillers alters this relationship. As seen in the interconnection between thickness and tensile index, moderate thickness increase due to fillers can support structural integrity up to a certain limit. However, beyond an optimal concentration, fiber bonding disruption leads to mechanical weakness despite increased thickness.

Tensile index, which measures resistance to breaking under tension, decreases as filler content increases. A moderate positive interdependence exists between thickness and tensile index, meaning that thicker paper should normally exhibit higher tensile strength. However, in filler-rich samples, this trend weakens as fiber bonds are disrupted. This pattern confirms that fillers act as structural gaps within the fiber matrix, limiting the formation of strong hydrogen bonds. The interdependence between tensile index and tear resistance further supports this, indicating that as tensile strength decreases, tear resistance also declines significantly.

Tear resistance depends on fiber length and network cohesion, both of which are negatively impacted by fillers. This is reflected in the strong negative interdependence between thickness and tear resistance. As thickness increases due to filler content, tear resistance drops significantly. CTMP control (199 mN) drops to 137 mN in CTMP B40Y, and NBSK control (839 mN) falls to 582 mN in NBSK B40Y. The interdependence between tensile index and tear resistance confirms that poor fiber bonding weakens both parameters simultaneously. However, moderate filler levels appear to maintain tear resistance better in CTMP-based sheets than in NBSK-based sheets. Notably, CTMP W15 (213 mN) even shows a slight increase over the control, suggesting that certain grain by-product fillers might reinforce tear resistance to some extent. This could be because of bran’s fibrous nature adding localized toughness, but at higher concentrations, this effect diminishes as fiber interconnectivity is compromised.

Bending stiffness, which determines the rigidity of the paper, also shows a decreasing trend with filler addition. This is reflected in the moderate interdependence between tensile index and bending stiffness, which confirms that as fiber strength is reduced, so is the overall structural rigidity. The data also suggests that grain by-product fillers may preserve stiffness better than wheat bran fillers, possibly due to differences in particle shape and filler-fiber interactions. However, at high concentrations, all fillers contribute to a significant loss of stiffness, making the material more flexible.

Unlike strength-related parameters, contact angle increases with filler addition, indicating improved hydrophobicity. Thickness and contact angle exhibit a moderate positive interdependence confirming that thicker, filler-enriched sheets tend to have better water resistance. A negative interdependence exists between tear resistance and contact angle, meaning that more hydrophobic structures tend to be weaker in tear strength.

3.4. Paper composite biodegradation stage

The material biodegradation stage is critical for evaluating how paper composites, particularly those with bran fillers, align with circular economy objectives by demonstrating their biodegradation efficiency. Applicable ISO biodegradability testing standards under aerobic and anaerobic conditions for packaging materials are outlined in EN 13432. ISO 14855 and ISO 14853 were selected for this study for the following reasons:

Relevance to biodegradable components: Paper composites incorporate biodegradable elements such as cellulose, starch, and proteins. These components share similar biodegradation pathways with bioplastics, making these standards directly applicable for assessing their behavior in both aerobic and anaerobic conditions.

Comprehensive evaluation: The standards provide robust methodologies to evaluate the ultimate biodegradability of organic carbon by measuring CO_2 evolution under aerobic conditions (ISO 14855) and biogas production under anaerobic conditions (ISO 14853). This aligns with the study's objective of understanding the environmental performance of the paper matrix and its fillers.

Laboratory equipment availability: The biodegradation laboratories at Politecnico di Milano operate according to these standards, ensuring the availability of the necessary equipment and expertise for testing.

3.4.1. Aerobic biodegradation

Aerobic biodegradation occurs in environments where oxygen is present, such as in composting systems. In this process, microorganisms use oxygen to break down organic materials, resulting in the production of carbon dioxide, water, and biomass. This method is particularly relevant for assessing how the materials would degrade in natural, oxygen-rich environments like soil or compost piles.

Table 15 summarizes the performed testing measurements related to the aerobic biodegradation process for different samples with bran filler and yeast additive. The key metrics include initial theoretical chemical oxygen demand (COD), COD (mg O_2/bottle) generated during incubation, final COD after deducting new microorganism growth, and calculated biodegradation efficiency.

Table 15. The aerobic test data

Substrate ID	Initial COD (mgO_2/bott)	COD demand from test (mgO_2/bott)	COD demand corrected (mgO_2/bott)	Initial COD (mgO_2/L)	COD demand from test (mgO_2/L)	Coefficient of Variation CV(%)	COD demand corrected (mgO_2/L)	Biodegradation Efficiency (%)
B15Y	1065.6	26.6	23.9	4910.7	122.4	7.1	110.2	2.2
B40	1077.0	48.6	43.8	4963	224.2	5.7	201.8	4.1
B40Y	1110.4	78.3	70.4	5117.1	360.7	3.8	324.6	6.3
Cellulose	1188.2	9.3	8.4	5475.6	43.0	17.3	38.7	0.7

Figure 18 shows the Biological Oxygen Demand (BOD) over 30 days. BOD indicates the oxygen required for microbial degradation of organic matter. All samples show biodegradation, with BOD values initially rising and then stabilizing.

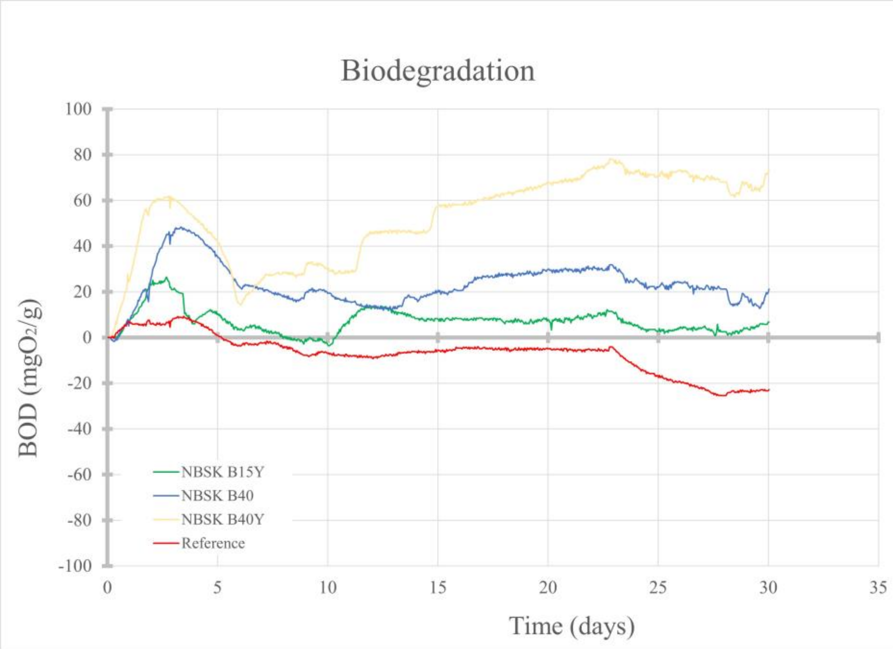


Fig. 18. BOD (mgO2/g) production in 30 days

The reference sample (red line) shows minimal change, indicating low biodegradation, consistent with the cellulose biodegradation efficiency of 0.7%. Wheat bran concentration notably impacts biodegradation due to its non-starch polysaccharides, which support microbial activity and provide essential nutrients[197] . The 15% wheat bran sample shows modest BOD increase and a biodegradation efficiency of 2.2%, while the 40% wheat bran sample has higher BOD and a 4% efficiency, indicating more efficient degradation with higher bran concentrations as it contains more available nutrients and structural polysaccharides[198] [199].

Yeast addition enhances biodegradation. The 40% wheat bran sample without yeast shows a 4% efficiency, while with yeast, it reaches 6.3%. *Saccharomyces cerevisiae* biomass is rich in proteins, vitamins, and minerals, which can be released into the environment and utilized by other microorganisms. These nutrients boost the growth and activity of bacteria and microbes involved in biodegradation, enhancing efficiency[200]. Additionally, yeast cells provide structural support and serve as a physical matrix for microbial colonization[201]. This physical presence facilitates a more effective breakdown of substrates by supporting microbial communities. The aerobic biodegradation testing revealed varying levels of efficiency depending on the filler content and the presence of yeast. The addition of yeast enhanced biodegradation efficiency, particularly in samples with higher bran content, by providing additional nutrients that support microbial activity. This suggests that incorporating bran fillers, especially in combination with yeast, could significantly improve the overall biodegradability of paper composites under aerobic conditions.

However, the cellulose reference exhibited minimal degradation, confirming the low degradability of pure cellulose under the specific test conditions used. This finding highlights the challenges associated with degrading pure cellulose aerobically and underscores the potential benefit of using bran fillers to enhance the biodegradability of cellulose-based materials.

Negative BOD values are uncommon but can arise because of experimental conditions and measurement methods[202]. The Oxitop system estimates oxygen consumption by measuring pressure changes, and since the test bottles were manually opened every five days for aeration, pressure fluctuations may have occurred, affecting readings. Each time the bottles were opened, oxygen was replenished, potentially altering microbial activity and leading to inconsistencies in pressure measurements. Additionally, the test setup included sodium hydroxide (NaOH) to absorb CO_2, and variations in CO_2 absorption rates could have influenced pressure changes, potentially leading to artificially low or negative BOD values. These factors highlight the importance of maintaining stable experimental conditions to ensure accurate BOD measurements.

Given that the cellulose reference showed minimal biodegradation, confirming its low degradability, it is recommended that for more accurate and reliable results, the aerobic biodegradation test should be repeated with some modifications. These include using a different inoculum, such as a compost with 40%-60% moisture content, which may better simulate natural composting conditions and enhance microbial activity. Additionally, testing equipment with an automatic oxygen supply should be used to ensure consistent oxygen availability throughout the testing period, which is critical for maintaining optimal conditions for aerobic degradation.

stent oxygen availability throughout the testing period, which is critical for maintaining optimal conditions for aerobic degradation.

If the reference material degrades by only 0.7% in 30 days, as observed in the initial test, the test is considered invalid, and these adjustments are necessary to obtain more accurate biodegradation data.

3.4.2. Anaerobic biodegradation

The difference in biodegradation processes underscores the importance of testing materials in both aerobic and anaerobic environments to gain a comprehensive understanding of their degradation behavior.

Anaerobic biodegradation takes place in environments devoid of oxygen, such as closed landfills or anaerobic digesters. In these conditions, microorganisms break down organic matter, producing methane (CH_4) and carbon dioxide as by-products. The importance of testing in anaerobic conditions lies in the understanding how the material would behave in oxygen-limited environments where methane production is a concern.

Table 16 summarizes the measurements related to the performed anaerobic biodegradation (BMP) process for samples with bran filler and yeast additive. Key metrics include Chemical Oxygen Demand (COD), theoretical and final methane (CH_4) production, and biodegradation efficiency.

Table 16. The anaerobic test data

Substrate ID	Initial COD (mgO_2/bot)	Theoretical CH_4 (mL/bott)	Initial COD (mgO_2/L	NET CH_4 Produced (mL/L)	Coefficient of Variation CV(%)	CH_4 Final (mL/L)	Theoretical CH_4 (mL/L)	Biodegradation Efficiency (%)
B15Y	2572	823.0	5358.3	1840.8	2.3	1656.8	1714.7	96.6
B40	2626	840.3	5470.8	1721.5	1.4	1549.3	1750.7	88.5
B40Y	2704	865.3	5633.3	1765.4	1.7	1588.9	1802.7	88.1
Cellulose	2832	906.2	5900.0	1726.9	16.7	1554.2	1888.0	82.3

Figure 19 shows the mean net cumulative gas production (NmL CH_4) over 30 days for the tested materials.

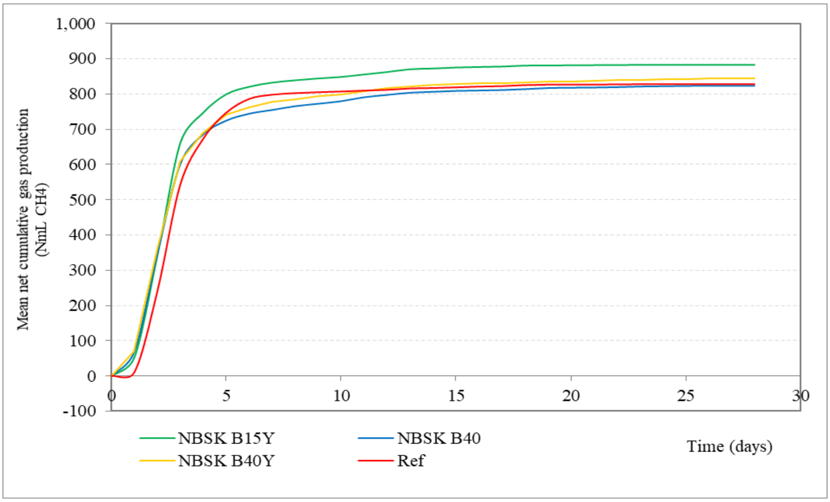


Fig. 19. Mean net cumulative gas production (NmL CH4) in 30 days

All samples exhibited rapid gas production within the first 5 days, followed by a plateau phase. The 15% bran filler with yeast additive sample showed the highest gas production (883.6 NmL CH_4), maintaining this level throughout the period. The 40% bran filler with yeast additive sample showed slightly lower gas production, indicating that higher bran content may reduce biodegradation efficiency.

Lower bran filler content (15%) with yeast additive is more efficient for biodegradation and methane production compared to higher bran content (40%). This efficiency difference is influenced by factors such as lignin content, which resists microbial degradation in the absence of oxygen[203 204 205 206]. Higher lignin content can inhibit biodegradation, decreasing with increasing lignin content[207].

Microbial synergy is another factor. Efficient biodegradation relies on interactions between microbial communities (bacteria, archaea, and fungi)[208 209 210]. A balanced substrate composition like 15% bran filler may support a more synergistic microbial environment compared to a higher bran content (40%).

Although increasing the bran filler content from 15% to 40% slightly reduces gas production in the presence of a yeast additive, both filler levels result in significantly higher gas production compared to the cellulose reference, indicating that cellulose alone is less effective for methane production than bran-based composites.

The NBSK B40 sample with 40% bran filler and no yeast additive showed slightly lower gas production (826.3 NmL CH_4) compared to NBSK B40Y, which is the same bran content with yeast additive (847.4 NmL CH_4), indicating a marginal positive effect of yeast on gas production. However, B40Y biodegradation efficiency is 88.1%, slightly lower than NBSK B40's 88.5%. This may be due to initial rapid degradation followed by incomplete overall degradation. Yeast additives can enhance initial microbial activity, rapidly breaking down accessible organic matter and producing significant gas early in the process. Once the easily degradable components are consumed, the remaining substrate may be less accessible or degradable, resulting in lower overall biodegradation.

The analysis indicates that while bran fillers enhance anaerobic biodegradation and methane production compared to cellulose alone, the efficiency of these processes is significantly influenced by the filler content and the presence of yeast additives. A lower bran content (15%) with yeast additive provides the best balance, resulting in higher biodegradation efficiency and methane production. However, as the bran content increases, the inhibitory effects of lignin become more pronounced, slightly reducing overall efficiency despite the initial boost provided by yeast. Lower bran content (15%) with yeast additive offers the best combination of biodegradation efficiency and methane production, making it a promising material for sustainable packaging applications. The most efficient material in aerobic conditions was the NBSK B40Y sample, which contained 40% bran filler combined with yeast additive.

The overall conclusions from the biodegradation testing stage suggest that paper composites with bran fillers, particularly when combined with yeast additives, exhibit improved biodegradability under both aerobic and anaerobic conditions compared to pure cellulose. These findings align with previous studies, which have shown that wheat bran and other grain by-products enhance biodegradation[211] [212] [213] by supplying essential nutrients and structural components that support and stimulate microbial activity. The study also highlights the need to optimize the balance between filler content and microbial activity to maximize biodegradability while minimizing environmental impact.

3.5. General result overview

The incorporation of wheat bran, grain by-product fillers and *Saccharomyces cerevisiae* into paper-based materials creates a multifaceted relationship between mechanical performance, hydrophobicity, biodegradation efficiency, and environmental performance. Increasing filler concentration results in a measurable decline in mechanical properties, as evidenced by reductions in tensile index, tear resistance, and bending stiffness. Although this reduction may limit the material's suitability for applications requiring high mechanical strength, such a trade-off is acceptable in single-use biodegradable packaging, where hydrophobicity, biodegradability, and environmental performance are prioritized.Beyond the effects of fillers, the incorporation of *Saccharomyces cerevisiae* further modified the physical and functional properties of the material. One of the most significant improvements associated with higher filler content, reinforced by yeast presence, is enhanced hydrophobicity. Filler and additive enriched paper samples exhibit greater water resistance, a crucial feature for food packaging applications aiming to replace conventional plastic coatings with bio-based alternatives.

The incorporation of wheat bran, grain by-product fillers, and *Saccharomyces cerevisiae* into biodegradable paper formulations influenced biodegradation efficiency. Higher filler concentrations introduce natural organic compounds that serve as an additional nutrient source for microbial activity, promoting faster material breakdown in composting environments. The presence of yeast enhances the material's compatibility with biological recycling systems, ensuring efficient decomposition within organic waste streams.

From an environmental perspective, the combined use of higher filler concentrations and *Saccharomyces cerevisiae* enhances the overall environmental performance of the material. One of the key environmental advantages of increasing filler content is the reduction of reliance on virgin raw materials, as by-products from agricultural and industrial processes replace a portion of primary fiber sources. This supports circular economy principles by utilizing renewable and secondary resources rather than extracting new ones. Additionally, because these by-products do not require intensive cultivation or separate processing, their incorporation into paper formulations reduces the overall energy consumption associated with production. *Saccharomyces cerevisiae* also presents promising potential as a bio-coating in biodegradable food packaging applications. This is particularly relevant in the replacement of fossil-based plastic coatings, where traditional moisture barriers introduce environmental concerns related to microplastic pollution and non-recyclability.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

1. The environmental performance criteria for single-use fast food packaging were defined as raw material savings, energy consumption reduction, recyclability, a shift toward renewable raw materials, lower chemical usage, and regional industrial symbiosis. The evaluation of bio-based alternatives identified wheat bran and wheat grain production residues as effective substitutes for virgin wood pulp, reducing reliance on primary resources and supporting circular material flows. *Saccharomyces cerevisiae* was identified as a viable bio-based material for enhancing barrier properties while maintaining compatibility with biological recycling processes.
2. A biodegradable packaging material prototype was created by incorporating wheat bran and wheat grain production residues to enhance biodegradability while maintaining the necessary mechanical and barrier properties for food

packaging applications. Experiments showed that up to 40% of primary raw material can be replaced with these alternatives. The addition of *Saccharomyces cerevisiae* improved biodegradability and hydrophobicity, opening possibilities for its application as a barrier coating.

3. Filler content negatively affected mechanical properties: tensile strength decreased by 19.8%, tear resistance by 12.3%, and bending resistance by 19.6%. On average, CTMP composites demonstrated moderate reductions in mechanical performance compared to the CTMP control: tensile strength decreased by 11.88%, tear resistance by 12.35%, and bending resistance by 19.10%. For NBSK-based composites, the changes were more pronounced: tensile strength decreased by 30.82%, tear resistance by 15.61%, and bending resistance by 25.74%, indicating a greater sensitivity of NBSK pulp to fillers.
4. Despite the negative impact on mechanical properties, eight filler-containing samples potentially met the material requirements for fast food packaging. The addition of *Saccharomyces cerevisiae* increased hydrophobicity by 11.95% without significantly impacting other mechanical properties. Both fillers and yeast additives enhanced biodegradation efficiency, particularly under aerobic conditions, where the highest biodegradation efficiency (183.04%) was achieved with 40% bran filler and yeast additive, and the average biodegradability increase reached 55.77%. Under anaerobic conditions, the highest biodegradation efficiency (96.62%) was observed in samples with 15% bran and yeast additive, with an overall biodegradability improvement of 12.44%. These results confirm the material's potential for single-use packaging and compatibility with biological recycling.
5. The results confirm that the developed single-use fast food packaging material integrates functional performance, biodegradability, and environmental efficiency, aligning with the principles of the circular economy and industrial symbiosis. The fillers used in the material reduce the demand for primary raw materials, enhance the efficiency of regional resource utilization, and contribute to the reduction of emissions generated during transportation. As these fillers do not require intensive cultivation or additional processing, their use also contributes to lowering overall energy and chemical consumption.

Recommendations

1. It is recommended to choose a closed-loop paper composite sheet production technology, which, due to the finest cellulose particles (micro and nano) remaining in the production process and the higher concentration of yeast, is likely to improve the physical-mechanical and barrier properties of the material.
2. It is recommended to investigate the yeast concentration in the sheet-forming mixture (wood pulp with fillers) and to study the impact of different yeast concentrations, such as 20wt% ir 30wt%, on the physical-mechanical and barrier properties of the material.
3. It is recommended to conduct aerobic biodegradability tests at a temperature of 50-60°C, using compost with 40%-60% moisture content as the inoculum, and to use testing equipment with automatic oxygen supply.

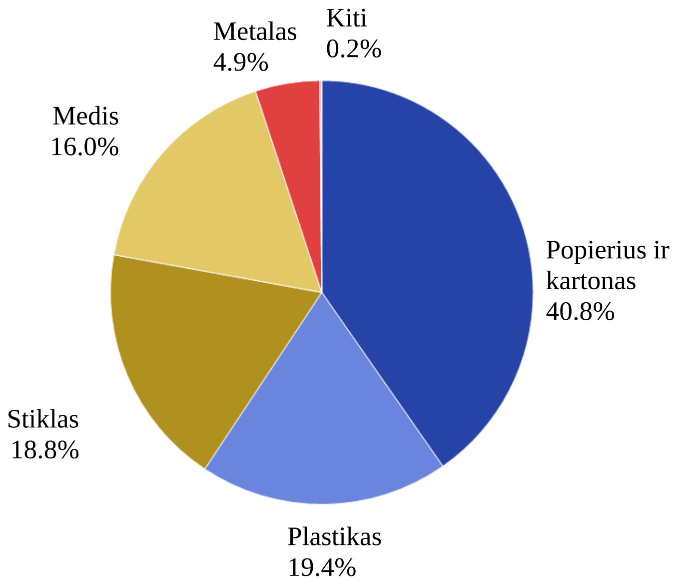
4. SANTRAUKA

4.1. Problemos aktualumas

Maistas ir maisto pakuotės yra kasdienio vartojimo produktai. Greitojo maisto vartojimo kultūra ir maistas išsinešimui yra neatsiejama šiuolaikinio gyvenimo būdo dalis. Remiantis „Statista“[7] duomenimis, Europos maisto pristatymo rinka 2025 m. siekia apie 45,38 milijardo eurų, o 2029 m. viršyti 50.9 milijardus eurų. Didėjanti greitojo maisto paklausa neatsiejamai didina vienkartinių pakuočių problemą, kuri jau tapo reikšmingu aplinkosaugos iššūkiu.

Visame pasaulyje 2023 m. buvo pagaminta 413.8 milijonų tonų plastiko[4], įskaitant vienkartines pakuotes, kurios sudaro apie 36,5 proc. šios produkcijos[5]. Dėl didėjančių elektroninės prekybos mastų ir augančios vartojimo kultūros popieriaus pakuočių gamybos apimtys 2023 m. pasiekė 258,74 milijono metrinių tonų[6]. Popierius ir plastikas yra pagrindinės pakuočių, įskaitant ir vienkartines, pramonėje naudojamos medžiagos.

Didėjantis pakuočių medžiagų naudojimas padidino ir pakuočių atliekų kiekį. Vien tik ES 2022 m. kiekvienam gyventojui teko apie 186,66[1] kg pakuočių atliekų. Lietuvoje šis skaičius siekė 151.12 kg. Kaip parodyta **20 paveiksle**, pagrindinį pakuočių atliekų ES srautą sudarė popierius ir kartonas – 34,0 milijonai tonų arba 40,8 proc. viso pakuočių atliekų srauto, atitinkamai Lietuvoje – 148,5 tūkstančiai tonų arba 34,7 proc.[2]. Toliau sekė plastikas, sudarantis 16,2 milijono tonų arba 19,4 proc. ES ir atitinkamai 107 tūkstančių tonų arba 25 proc.[3] Lietuvoje.



20 pav. Pakuočių atliekų kiekiai pagal pakuotės medžiagą, ES 2022 (proc. %)

Pakuočių perdirbimo rodikliai tiek ES, tiek Lietuvoje ženkliai skiriasi priklausomai nuo medžiagos. 2022 m. popieriaus ir kartono pakuočių perdirbimo rodiklis buvo ypač aukštas – 83,1 proc. ES ir 81,1 proc. Lietuvoje[8], tuo tarpu plastiko pakuočių perdirbimo rodiklis tebuvo kiek daugiau nei 40,7 proc. ES ir atitinkamai 44,1 proc. Lietuvoje[9]. Visame pasaulyje perdirbama tik 9 proc. plastiko atliekų[10]. Didžioji plastiko atliekų dalis, t. y. apie 79 proc.[11], kaupiama sąvartynuose, teršia vandenynus ir kitas ekosistemas, sukeldama ilgalaikę ekologinę žalą ir sąlygodama biologinės įvairovės praradimą[12] [13] [14].

Siekdama sumažinti vienkartinio plastiko poveikį aplinkai ES įgyvendina įvairias priemones, tarp kurių yra tam tikrų vienkartinių plastikinių gaminių draudimai ir reikalavimai didinti perdirbimą bei gerinti atliekų tvarkymo praktiką. Konkretūs tikslai apima atskirą surinkimą ir perdirbto plastiko kiekio didinimą naujuose gaminiuose[15], plastiko pakuotės atliekų perdirbimas iki 2025 m. turi pasiekti 50 proc., o iki 2030 m. 55 proc.[16]. Tikslai nustatyti ir popieriaus bei kartono pakuočių perdirbimui – iki 2025 turi būti perdirbama 75 proc., o iki 2030 m. 85 proc. popieriaus ir kartono pakuočių atliekų.

Be plastiko, popieriaus ir kartono perdirbimo tikslų, platesnis žiedinės ekonomikos kontekstas pabrėžia ir biologinio perdirbimo svarbą. 2018 m. ES direktyvoje (ES) 2018/851[17] yra skatinamas biologinis perdirbimas, įskaitant kompostavimą ir anaerobinį skaidymą, taip papildant mechaninio perdirbimo ciklą. Šie procesai atlieka itin svarbų vaidmenį mažinant atliekų kiekį, atkuriant dirvožemio kokybę ir gaminant atsinaujinančią energiją. ES bioekonomikos strategijoje[18] taip pat akcentuojama biologinio ciklo svarba uždarant medžiagų srautus – tai užtikrina, kad biologiškai skaidžios medžiagos būtų efektyviai sugrąžinamos į natūralią aplinką, o ne prarandamos kaip atliekos. Integruodama tiek mechaninį, tiek ir biologinį ciklus, žiedinės ekonomikos koncepcija leidžia maksimaliai efektyviai naudoti išteklius ir minimizuoti poveikį aplinkai.

Toks požiūris atsispindi ir Lietuvos nacionalinėje politikoje. „Lietuvos pramonės perėjimo prie žiedinės ekonomikos kelrodžio“[19] dokumente perdirbimas, įskaitant ir biologinį perdirbimą, įvardijamas kaip prioritetinė sritis, siekiant švaresnės ir konkurencingesnės pramonės, atitinkančios tvarios ateities ekonomikos poreikius. Tikslams pasiekti būtina ne tik efektyvinti atliekų surinkimo ir perdirbimo sistemas, bet ir taikyti žiedinės ekonomikos principus, akcentuojant optimalų žaliavų parinkimą bei tvarų išteklių valdymą. Taip pat svarbu optimizuoti pakuočių gyvavimo ciklo pabaigą ir mažinti neigiamą poveikį aplinkai – minimizuoti vizualinę ir mikroplastikų taršą maisto vertės grandinėje[20].

Didėjantis vartojimas ir neigiamas vienkartinių pakuočių, pagamintų iš įprasto plastiko, poveikis aplinkai paskatino ieškoti tvaresnių alternatyvų. Viena iš galimybių yra bioplastikų, gaminamų iš atsinaujinančių šaltinių, panaudojimas[21]. Šios medžiagos gali žymiai sumažinti ir priklausomybę nuo iškastinio kuro, ir anglies pėdsaką[2]. Bioplastikai jau yra naudojami maisto pakuočių sektoriuje – iš jų gaminami puodeliai, maisto dėžutės ir lėkštės, stalo įrankiai[23], kurie gali būti tiek vienkartiniai, tiek daugkartiniai. Yra apskaičiuota, jog pakeitus įprastus plastikus bioplastikais, būtų ženkliai – 241–316 milijonų tonų CO_2 ekvivalento per metus[24] – sumažintos šiltnamio efektą sukeliančių dujų emisijos ir mikroplastiko tarša.

Popierinės pakuotės, gaminamos iš tvariai tvarkomų miškų medienos, yra dar viena alternatyva. Pažangios popieriaus gamybos technologijos leidžia sumažinti popieriaus pramonės poveikį aplinkai ir optimizuoti žaliavų, energijos ir vandens sąnaudas[25]. Ne medienos pluoštų, pavyzdžiui, gaunamų iš žemės ūkio šalutinių produktų arba žemės ūkio produktų apdirbimo atliekų, tokių kaip grūdų šiaudai ar lukštai[26], naudojimas prisideda prie aplinkosauginio poveikio mažinimo[27]. Naudodama šalutinius produktus, kurie kitaip būtų laikomi atliekomis, popieriaus pramonė gali sumažinti priklausomybę nuo medienos pluoštų, mažinti miškų kirtimą ir iškastinio kuro vartojimą, taip prisidėdama prie tvaresnės žiedinės ekonomikos. Papildomai tokie žemės ūkio šalutiniai produktai nereikalauja papildomų žemės plotų auginimui, todėl yra efektyvi ir tvari popieriaus gamybos žaliava.

Vienkartinių maisto pakuočių sektorius susiduria su keletu esminių iššūkių. Pirmiausia tai optimalus tvarių medžiagų pasirinkimas, kuris ne tik leistų taupyti pirmines žaliavas, bet ir efektyviai integruoti pakuočių atliekas į žiedinės ekonomikos ciklus gyvavimo ciklo pabaigoje taip mažinant poveikį aplinkai. Antrasis iššūkis yra susijęs su vienkartinių maisto pakuočių barjerinėmis savybėmis. Maisto pakuočių medžiaga ar jų danga turi užtikrinti tinkamas maisto apsaugos barjerines savybes ir tuo pačiu nesumažinti vienkartinių pakuočių perdirbamumo galimybių jų gyvavimo ciklo pabaigoje. Siekiant užtikrinti reikiamas barjerines savybes, tradicinė plastikinė maisto pakuotė dažnai sudaryta iš kelių medžiagų sluoksnių, o tai itin apsunkina mechaninį perdirbimą arba padaro jį apskritai neįmanomą[28]. Net jei pakuotė pagaminta iš vienos rūšies medžiagos, bet yra užteršta maisto atliekomis, ji tampa neperdirbama arba nepageidaujama perdirbimo cikle – nešvari medžiaga daro neigiamą įtaką bendrai perdirbamos medžiagos kokybei, kuri yra esminė perdirbimo procese. Popierinėms pakuotėms keliami panašūs perdirbimo iššūkiai. Popierius paprastai neturi tinkamų barjerinių savybių[29] [30], reikalingų maisto pakuotėms, todėl dažnai yra dengiamas riebalams, vandeniui ir deguoniui atspariomis / nepralaidžiomis dangomis, kurios gaminamos iš iškastinio kuro išteklių, tokių kaip polietilenas (PE), polivinilo alkoholis (PVOH), polifluoroalkilinės medžiagos (PFAS)[31] [32]. Tačiau nors tokiomis dangomis padengtas popierius atitinka maisto pakuotėms keliamus barjerinius reikalavimus, jis nėra nei mechaniškai, nei biologiškai perdirbamas, todėl didina tiek susidarančių atliekų kiekius, tiek mikroplastiko taršą[27]. Įprastai plastiku dengtos popieriaus pakuotės mikroplastiką išskiria tiek naudojimo metu[33] [34], tiek gyvavimo ciklo pabaigoje[35] [36]. Mechaninis poveikis, UV spinduliuotė bei cheminės reakcijos šias dangas suskaido į mikroplastiko daleles, kurios ilgai išlieka aplinkoje, kaupiasi maisto grandinėje ir kelia grėsmę gyvūnų ir žmonių sveikatai. Nors PVOH (polivinilo alkoholis), kitaip nei PE, tam tikromis sąlygomis laikomas biologiškai skaidžiu, nepilnas jo skaidymasis natūralioje aplinkoje kelia abejonių dėl galimos mikroplastiko taršos[37]. Jei PVOH visiškai nesusiskaido į CO_2, vandenį ir biomasę, likusios dalelės gali patekti į ekosistemas, todėl jo tvarumo vertinimas išlieka abejotinas[38]. Maistu užterštos popieriaus pakuotės dėl žemos pluošto kokybės mechaniškai neperdirbamos[39], dėl savo biologinės kilmės jos itin efektyviai galėtų būti nukreipiamos į biologinio perdirbimo srautus[40]. Tačiau tokios pakuotės turėtų būti padengtos natūralia biologinės kilmės danga.

4.2. Darbo tikslas ir uždaviniai

Disertacijos tikslas – sukurti žiedinės ekonomikos principus atitinkančią, biologiškai skaidžią vienkartinės greitojo maisto pakuotės medžiagą, pagamintą tik iš atsinaujinančių žaliavų ir priedų, skatinančių biologinį skaidumą, ir išanalizuoti šios medžiagos aplinkosauginius aspektus bei fizikinius-mechaninius ir biologinio skaidumo parametrus.

Uždaviniai:

1. nustatyti vienkartinės pakuotės aplinkosauginio efektyvumo ir integracijos į žiedinę ekonomiką kriterijus, atsižvelgiant į žaliavų kilmę, perdirbimą ir biologinį skaidumą, bei identifikuoti optimalias alternatyvias žaliavas ir dangas, kurios gali pakeisti tradicinius komponentus;
2. sukurti biologiškai skaidžios pakuotės medžiagos prototipą, integruojant atsinaujinančias biologinės kilmės žaliavas ir priedus, kurie skatina biologinį skaidumą, kartu užtikrinant reikiamas mechanines bei barjerines savybes;
3. ištirti sukurtos medžiagos prototipo fizikines-mechanines ir barjerines savybes, atlikti medžiagos prototipo aerobinio ir anaerobinio skaidumo tyrimus;
4. įvertinti ir apibendrinti sukurtos pakuotės medžiagos aplinkosauginio efektyvumo, fizikinių-mechaninių savybių ir biologinio skaidumo efektyvumo tyrimų rezultatus, atsižvelgiant į žiedinės ekonomikos principų įgyvendinimą tiek žaliavų parinkimo, tiek pakuočių atliekų tvarkymo etapuose.

Ginamieji teiginiai:

1. vienkartinės popierinės maisto pakuotės gamyboje iki 40 proc. pirminės medienos plaušienos žaliavos galima pakeisti žemės ūkio sektoriaus šalutiniais gamybos produktais, kurių naudojimas įgalina pramoninės simbiozės principą ir padidina medžiagos žiediškumą, išlaikant funkcines savybes;
2. *Saccharomyces cerevisiae* (kepimo / alaus mielės) gali pagerinti kuriamos vienkartinio panaudojimo maisto pakuotės medžiagos barjerines savybes ir padidinti jos biologinio skaidumo efektyvumą.

4.3. Tyrimo objektas

Tyrimo objektas – biologiškai skaidi greitojo maisto pakuočių medžiaga, atitinkanti žiedinės ekonomikos principus, sukurta naudojant atsinaujinančias biologinės kilmės žaliavas – kviečių sėlenas ir šalutinius kviečių grūdų perdirbimo produktus. Disertacijoje yra analizuojama galimybė iš dalies pakeisti pirminę medienos plaušieną nemedieninės kilmės šalutiniais žemės ūkio produktais, tiriamas *Saccharomyces cerevisiae* mielių, kaip funkcinio priedo, poveikis medžiagos barjerinėms savybėms ir biologiniam skaidumui.

4.4. Mokslinis naujumas ir praktinis pritaikymas

Šioje disertacijoje pateikiamas novatoriškas mokslinis požiūris į biologiškai skaidžių vienkartinių maisto pakuočių medžiagų kūrimą, integruojant nemedieninės kilmės žemės ūkio šalutinius produktus ir *Saccharomyces cerevisiae* (kepimo / alaus mieles) į popieriaus pagrindo kompozitines pakuotės medžiagas. Darbe pateikiamos naujos įžvalgos apie vienkartinių maisto pakuočių medžiagų kūrimą, vadovaujantis žiedinės ekonomikos principais:

1. pirminės medienos plaušienos pakeitimas nemedieninės kilmės grūdų perdirbimo šalutiniais produktais. Tyrimo rezultatai rodo, kad iki 40 proc. pirminės medienos plaušienos galima pakeisti nemedieninės kilmės žemės ūkio šalutiniais produktais, taip skatinant pramoninę simbiozę, didinant medžiagos žiediškumą ir kartu išlaikant reikiamas funkcines savybes;
2. funkcinis Saccharomyces cerevisiae pritaikymas biologiškai skaidžioje pakuotėje. Tyrime įvertintas Saccharomyces cerevisiae mielių kaip biologinės kilmės funkcinio priedo poveikis kompozitinės medžiagos barjerinėms savybėms ir biologinio skaidumo efektyvumui – tai iki šiol mažai nagrinėta tyrimų kryptis pakuočių medžiagų srityje;
3. biologiškai skaidžios pakuotės medžiagos sukūrimas ir eksperimentinis pagrindimas. Disertacijos metu sukurtas ir eksperimentiniais tyrimais pagrįstas biologiškai skaidaus popieriaus pagrindo medžiagos prototipas pasižymi tinkamomis funkcinėmis, barjerinėmis savybėmis ir biologiniu skaidumu. Sukurta pakuotės medžiaga gali būti vertinama kaip perspektyvi alternatyva tradicinėms plastiku dengtoms popierinėms pakuotėms, atitinkanti žiedinės ekonomikos principus.

Disertacijos praktinis pritaikymas grindžiamas pateiktomis įžvalgomis ir atliktų eksperimentinių tyrimų rezultatais, kurie sudaro pagrindą tolesniam pakuotės medžiagos plėtojimui bei jos pritaikymui pramoninės gamybos procesuose.

Žaliavų panaudojimas ir žiediškumas. Atlikti tyrimai pagrindžia galimybę pirminę medienos plaušieną iš dalies pakeisti nemedieninės kilmės grūdų perdirbimo šalutiniais produktais, taip prisidedant prie efektyvesnio išteklių naudojimo ir pramoninės simbiozės principų įgyvendinimo.

Iškastinės kilmės dangų eliminavimas. Sukurtam medžiagos prototipui būdingas potencialas tapti biologiškai skaidžia alternatyva plastiku dengtoms popieriaus pakuotėms. Medžiaga tinkama biologiniam perdirbimui, įskaitant pramoninį kompostavimą ir anaerobinį skaidymą. Vis dėlto, siekiant visiško funkcionalumo, būtinas tolesnis barjerinių savybių optimizavimas.

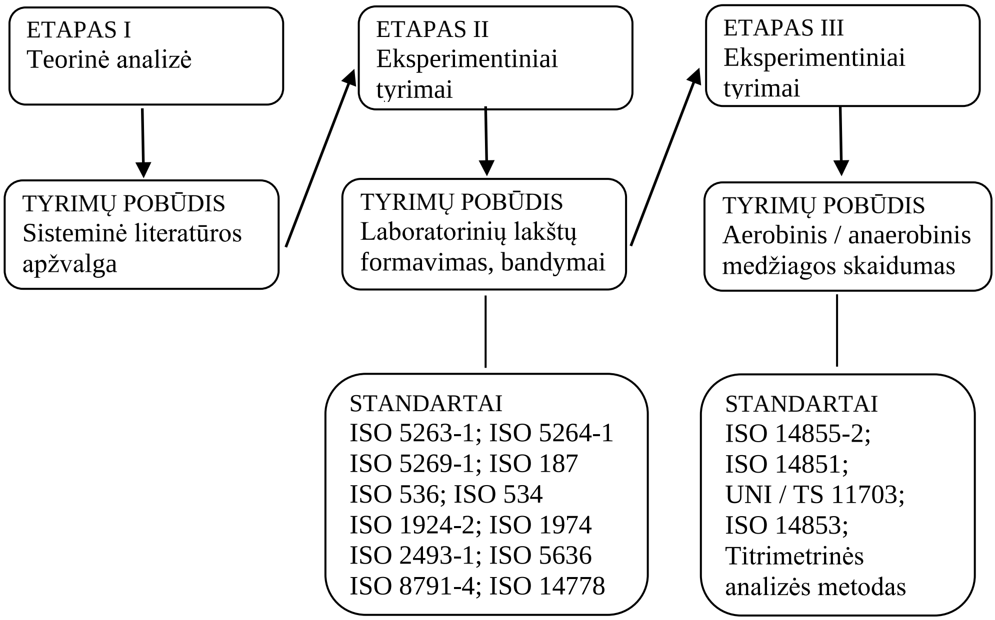
Pramoninio pritaikymo potencialas. Nors eksperimentiniai tyrimai buvo atlikti laboratoriniu lygmeniu, gauti rezultatai suteikia mokslinį pagrindą medžiagos sudėties optimizavimui ir tolimesniam jos pritaikymui pramoniniuose gamybos procesuose.

Regioninių išteklių panaudojimo nauda. Vietoje prieinamų grūdų perdirbimo šalutinių produktų naudojimas skatina efektyvesnį išteklių panaudojimą ir prisideda prie regioninės ekonomikos stiprinimo, sudarydamas prielaidas naujoms šių medžiagų (atliekų) panaudojimo galimybėms.

Atitiktis strateginėms kryptims ir teisiniam reguliavimui. Sukurtas pakuotės medžiagos prototipas atitinka tiek Europos Sąjungos, tiek nacionalinės politikos ir strategines kryptis, susijusias su plastiko vartojimo mažinimu, žiedinės ekonomikos plėtra ir perėjimu prie aplinkai palankių pakuočių sprendimų.

4.5. Tyrimų metodologija

Disertacijos metu buvo atlikta teorinė analizė bei eksperimentiniai tyrimai, kurių struktūra, taikyti standartai ir metodai pateikti **21 paveiksle**. Siekiant identifikuoti tyrimų kontekstą ir suformuoti metodologinį pagrindą tolimesniems eksperimentiniams tyrimams pirmame etape atlikta sisteminė literatūros apžvalga. Eksperimentinėje dalyje buvo vykdomi laboratoriniai tyrimai, apimantys žaliavų paruošimą, laboratorinių lakštų formavimą, fizikinių–mechaninių bei barjerinių savybių tyrimus, taip pat aerobinio ir anaerobinio skaidumo vertinimą.



21 pav. Disertacijos etapų ir tyrimų shema

I etapo sisteminė literatūros apžvalga apėmė žiedinės ekonomikos principų, žiedinio produktų dizaino, atliekų ir išteklių valdymo strategijų bei jų taikymo maisto pakuočių sektoriuje analizę. Moksliniai šaltiniai atrinkti naudojant raktažodžius „žiedinės ekonomikos strategijos“, „žiedinis produktų dizainas“, „žiedinės maisto pakuotės“ ir „atliekų tvarkymo strategijos“, pasitelkiant Scopus, ResearchGate, ScienceDirect ir Google Scholar duomenų bazes bei Ellen MacArthur Foundation, European Bioplastics ir Zero Waste Europe ataskaitas.

II etape buvo atliekamas eksperimentinis biologiškai skaidžios pakuotės medžiagos prototipo kūrimas, naudojant atrinktas žaliavas: medienos plaušieną, šalutinių grūdų apdirbimo produktų užpildus ir *Saccharomyces cerevisiae* priedą. Šiame etape buvo tiriamos prototipo fizikinės ir mechaninės savybės, bandymai atlikti Lappeenranta-Lahti technologijos universiteto (LUT) Energetikos sistemų mokyklos Mechanikos inžinerijos katedroje (Lappeenranta, Suomija).

III etape atlikti sukurtos pakuotės medžiagos prototipo aerobinio ir anaerobinio skaidumo tyrimai. Aerobiniai tyrimai vykdyti Milano politechnikos universiteto DICA LIA laboratorijoje (Milanas, Italija), o anaerobiniai – Aplinkos inžinerijos A. Rozzi laboratorijoje (FabE-lab), Kremonoje, Italijoje.

17 lentelėje pateikami eksperimentinių tyrimų etapai, tyrimuose naudoti standartai ir metodai bei aprašai.

17 lentelė. Eksperimentinių tyrimų etapai, standartai ir metodai

Etapas	**Standartas, metodas**	**Aprašas**
Žaliavų paruošimas.	Sausosios medžiagos kiekio nustatymas	Medžiagų drėgmės nustatymas naudojant Precisa 310M/HA300.
	ISO 5263-1[147]	Plaušiena. Laboratorinis šlapiasis skaidymas. 1 dalis. Cheminės plaušienos skaidymas.
	ISO 5264-1[148]	Plaušiena. Laboratorinis malimas. 1 dalis. „Valley Beater“ metodas.
Lakštų formavimas – 23 bandiniai.	ISO 5269-1[149]	Plaušiena. Laboratorinių lakštų paruošimas fizikiniams bandymams. 1 dalis. Standartinis formuotuvo metodas.
	ISO 187[150]	Popierius, kartonas ir plaušiena. Standartinė kondicionavimo ir bandymo aplinka, jos reguliavimo ir bandinių kondicionavimo metodika.
	ISO 536[151]	Popierius ir kartonas. Gramatūros nustatymas.
	ISO 534[152]	Popierius ir kartonas. Storio, tankio ir savitojo tūrio nustatymas.
Fizikinių-mechaninių savybių tyrimai – 20 bandinių.	ISO 1924-2[153]	Popierius ir kartonas. Savybių nustatymas tempiant. 2 dalis. Pailgėjimo tempiant pastoviu greičiu metodas (20 mm/min).
	ISO 1974[154]	Popierius. Atsparumo plėšimui nustatymas. Elmendorfo metodas.
	ISO 2493-1[155]	Popierius ir kartonas. Atsparumo lenkimui nustatymas.
	ISO 5636[156]	Popierius ir kartonas. Oro pralaidumo nustatymas. Bendtseno metodas.
	ISO 8791-4[157]	Popierius ir kartonas. Paviršiaus šiurkštumo nustatymas.
	ISO/TS 14778[158]	Popierius ir kartonas. Vandens kontaktinio kampo matavimas optiniais metodais.
Biologinio skaidumo tyrimai – 3 bandiniai.	ISO 14855-2[159]	Plastikai. Visiško aerobinio biologinio skaidumo nustatymas valdomomis kompostavimo sąlygomis. Išsiskyrusio anglies dioksido analizės metodas. 2 dalis. Anglies dioksido, išsiskyrusio laboratorinio bandymo metu, gravimetrinis matavimas

	ISO 14851[160]	Plastikai. Visiško aerobinio biologinio skaidumo vandens terpėje nustatymas. Metodas matuojant deguonies suvartojimą uždarame respirometre.
	UNI/TS 11703[161]	Susidarančio metano kiekio nustatymo metodas vandens terpėje.
	ISO 14853[162]	Plastikai. Plastikinių medžiagų galutinio anaerobinio biologinio skaidymo vandeninėje sistemoje nustatymas. Biodujų gamybos matavimo metodas.
	Cheminio deguonies suvartojimas (COD)[163]	Dikromato metodas titruojant.

Žaliavų paruošimas

Balinta spygliuočių (NBSK) plaušiena, pagaminta iš pušies ir eglės, buvo gauta iš Billerud (Solna, Švedija), o iš tuopos pagaminta chemotermomechaninė plaušiena (CTMP) gauta iš Sicem Saga (Reggio Emilia, Italija). Abi žaliavos turi FSC sertifikatą, patvirtinantį, jog plaušiena pagaminta laikantis atsakingo miškų valdymo reikalavimų. Medžiagos turi tinkamumo sąlyčio su maistu sertifikatus. Fizikiniai-mechaniniai plaušienų parametrai pateikti **18 lentelėje**.

18 lentelė. Fizikinės-mechaninės naudotos plaušienos savybės

Savybė	**Mato vnt.**	**CTMP**	**NBSK**
Plaušo ilgis	mm	1,5	1,9–2,1
Tempimo indeksas	Nm/g	min 25	110
Trūkio indeksas	kPa m²/g	1,2	8,2
Atsparumo plėšimui indeksas	mN m²/g	6,8	8,5

Kviečių grūdų apdirbimo šalutiniai produktai (juos sudaro kviečių, rugių, speltos lukštų, smulkių grūdų, šiaudų, žolių sėklų liekanos ir grūdų dulkės) ir kviečių sėlenos (išorinė kviečių grūdo luobelė) buvo įsigytos iš Malsena Plius (Vievis, Lietuva). Sausos alaus mielės (*Saccharomyces cerevisiae*) SafAle™ S-33 buvo įsigytos iš Fermentis (Marquette-lez-Lille, Prancūzija), o cukrus iš Nordic Sugar (Kėdainiai, Lietuva).

Medžiagų sausoji masė (žr. **19 lentelę**) buvo nustatyta naudojant drėgmės analizatorių Precisa 310M/HA300. Popieriaus užpildų frakcijų sudėtis (žr. **20 lentelę ir 22 paveikslą**) buvo nustatyta naudojant 500 µm, 250 µm, 150 µm ir 75 µm sietus. Popieriaus kompozito gamybai buvo naudojama originali užpildo sudėtis, t. y. visos užpildų frakcijos.

19 lentelė. Nustatytas sausos medžiagos kiekis, proc.

Žaliava	**Sausos medžiagos kiekis, proc.**
Balinta spygliuočių plaušiena (NBSK)	93,55
chemotermomechaninė plaušiena (CTMP)	91,1

Grūdų apdirbimo liekanos	87,25
Kviečių sėlenos	92,54
Mielės (*Saccharomyces cerevisiae*)	98,78
Cukrus	99,89

20 lentelė. Užpildų frakcijų kompozicija, proc.

Žaliava	**500µm**	**250µm**	**150µm**	**75µm**	**>75µm**
Grūdų apdirbimo liekanų frakcija, proc.	43,9	23,9	11,6	12,4	8,3
Kviečių sėlenų frakcija, proc.	99,5	0,4	0,1	-	-

22 pav. 1-5 išsijotos kviečių apdirbimo šalutinių produktų frakcijos, 6-8 sėlenų frakcijos

Plaušiena paruošta pagal ISO 5263-1 standartą – skaidoma 10 000 apsisukimų greičiu 5 minutes, o paskui pagal ISO 5264-1 standarto reikalavimus 30 minučių malama Valley Beater įrenginyje, veikiančiame 10 000 apsisukimų greičiu. Vadovaujantis gamintojo pateiktomis rekomendacijomis CTMP plaušiena prieš skaidymą 20 minučių buvo mirkoma 40 °C temperatūros vandenyje.

Siekiant imituoti alaus gamybos porceso metu vykstančius procesus[164] [165] ir užtikrinti žaliavos mikrobiologinį saugumą, grūdų perdirbimo atliekos ir kviečių sėlenos 10 minučių buvo virinamos 100 °C temperatūroje[166] [167]. Sausos alaus mielės (*Saccharomyces cerevisiae*) buvo aktyvuotos skystoje plaušienos suspensijoje su sterilizuotomis grūdų apdirbimo atliekomis ir cukrumi bei 14 valandų laikomos 23°C temperatūroje. Sausos plaušienos mišinio, cukraus ir mielių santykis buvo – 10:2:1[168].

Popieriaus kompozito lakštų formavimas ir bandinių savybių tyrimas

Iš viso buvo paruošti 23 skirtingos medžiagos formulės bandiniai (žr. **21 lentelę**) su 15 wt% ir 40 wt% užpildais bei 10 wt% mielių priedu. Šių mėginių paruošimas vyko vadovaujantis ISO 5269-1:2005 standartu. 60 g/m^2 bandinių lakštai formuoti vadovaujantis standartinio lakštų formuotuvo metodu.

Siekiant įvertinti mielių išplovimo riziką standartinio laboratorinio lakštų formavimo proceso metu, papildomai buvo paruošti trys bandiniai naudojant uždaro ciklo lakštų formavimo metodą (žr. **21 lentelę**). Tiek taikant standartinį laboratorinių lakštų formavimo metodą, tiek uždarojo ciklo metodą, kiekvieno atskiro popieriaus lakšto formavimo metu vanduo iš lakšto formavimo cilindro yra išleidžiamas, taip ant lakštų formavimo grotelių iš plaušienos kompozito masės suformuojant bandinį. Siekiant išvengti kietųjų dalelių (pvz., nanoceliuliozės ar kitų mikropriemaišų) formuojant naują lakštą ir taikant standartinį lakštų formavimo metodą, į formavimo cilindrą buvo prileidžiama naujo iš vandens sistemos tiekiamo vandens. Tuo tarpu uždaro ciklo lakštų formavimo metodas leido tą patį procesinį vandenį panaudoti formuojant kitus lakštus, o tai reiškia, kad cikle liko cirkuliuoti tiek mikropriemaišos, tiek mielių priedas. Kiekvieno uždaro ciklo metu buvo pagaminama po 10 lakštų. Pirmieji trys lakštai buvo suformuoti kaip ciklo stabilizavimo fazės bandiniai ir į parametrų analizę įtraukti nebuvo.

Paruošti lakštai sudėti „sumuštinio principu“ su džiovinimo bloteriais (kurie sugėrė lakštuose likusį vandenį) ir presavimo plokštelėmis automatiniu presu buvo presuojami 4 minutes esant 490 kPa slėgiui. Presuoti lakštai 90 minučių džiovinti džiovinimo būgne, kurio paviršiaus temperatūra siekė apytiksliai 78°C.

21 lentelė. Popieriaus kompozito medžiagos kompozicija ir lakštų formavimo metodas

Bandinio kompozicija (plaušienos rūšis ir užpildo kiekis)	**Įprastinis lakštų gamybos metodas, be mielių**	**Įprastinis lakštų gamybos metodas su 10 proc. mielių priedu**	**Uždaro ciklo lakštų gamyba, be mielių**	**Uždaro ciklo lakštų gamyba su 10 proc. mielių priedu**
NBSK	NBSK	NBSK Y	NBSK loop	NBSK Y loop
NBSK su grūdų apdirbimo atliekomis, 15 wt%	NBSK W15	NBSK W15Y	-	-
NBSK su sėlenų užpildu, 15 wt%	NBSK B15	NBSK B15Y	-	NBSK B15Y loop
NBSK su grūdų apdirbimo atliekomis, 40 wt%	NBSK W40	NBSK W40Y	-	-
NBSK su sėlenų užpildu, 40 wt%	NBSK B 40	NBSK B 40Y	-	-
CTMP	CTMP	CTMP Y	-	-
CTMP su grūdų apdirbimo atliekomis, 15 wt%	CTMP W15	CTMP W15Y	-	-
CTMP su grudų apdirbimo atliekomis, 40 wt%	CTMP W40	CTMP W40Y	-	-
CTMP su sėlenų	CTMP B15	CTMP B15Y	-	-

užpildu, 15 wt%				
CTMP su sėlenų užpildu, 40 wt%	CTMP B40	CTMP B40Y	-	-

Išdžiovinti bandiniai pagal ISO 187 standartą buvo kondicionuoti ir automatine pjaustykle supjaustyti 141x141 mm formatu. Supjaustytų bandinių gramatūra buvo matuojama pagal ISO 536, lakštų storis buvo įvertintas pagal ISO 534. Atsparumo tempimui savybės matuotos vadovaujantis ISO 1924, atsparumo plyšimui ISO 1974, o atsparumo lenkimui – ISO 2493-1 standartais.

Barjerinės oro pralaidumo savybės nustatytos naudojant Bendtseno metodą vadovaujantis ISO 5636, o paviršiaus šiurkštumas išmatuotas pagal ISO 8791 standartą. Popieriaus hidrofobiškumas buvo tiriamas kontaktinio kampo matavimo optiniu metodu pagal ISO/TS 14778 standartą – ant bandinio paviršiaus buvo užlašintas tiksliai kontroliuojamo 1 µl tūrio vandens lašas, naudojant vaizdų analizės programinę įrangą fiksuota skysčio ir paviršiaus sąveika. Duomenų analizei naudota lašo kontaktinio kampo vertė, užfiksuota praėjus 0,1 sekundės nuo lašo kontakto su paviršiumi momento. Matavimai atlikti trijose skirtingose bandinio zonose – užpildo zonoje, zonoje be užpildo ir atsitiktinėje zonoje, matavimai atlikti abiejose lakšto pusėse (vidinėje ir išorinėje).

Popieriaus kompozito lakštų biologinio skaidumo tyrimai

II tyrimų etape bandiniai su geriausiomis hidrofobinėmis savybėmis (žr. **22 lentelę**) buvo pasirinkti tolesniems aerobinio ir anaerobinio skaidumo tyrimams. Siekiant įvertinti sėlenų užpildo ir mielių įtaką biologinio skaidumo efektyvumui, pasirinkti skirtingos užpildo koncentracijos bandiniai bei bandiniai su mielių priedu ir be jų.

22 lentelė. Bandiniai, atrinkti biologinio skaidumo tyrimams

Bandinio ID	**Sėlenų užpildas (proc.)**	**Saccharomyces cerevisiae**
NBSK B15	15	Ne
NBSK B15Y	15	Taip
NBSK B40	40	Ne
NBSK B40Y	40	Taip

Kompostas, naudotas aerobiniams tyrimams, buvo gautas iš kompostavimo įmonės (šiaurės Milano regionas), kurioje apdorojamos biologinės (žaliosios ir maisto) atliekos. Anaerobinis inokuliatas buvo paimtas iš termofilineiėje 50 °C temperatūroje veikiančio nuotekų valymo įrenginio (Como regionas).

Prieš pradedant biologinio skaidumo tyrimus buvo nustatytas popieriaus kompozito bandinių sausosios medžiagos (SM) ir lakiųjų medžiagų kiekis bei taikant dichromato metodą nustatytas ir apskaičiuotas cheminis deguonies poreikis (ChDs).

Aerobinio skaidumo tyrimai

Kaip inokuliatas aerobinio skaidumo tyrimams naudotas aeruotas kompostas, kurio pradinis anglies ir azoto (C:N) santykis 25–30:1, o pH 7. Kompostas paruoštas laikantis ISO 14855-2 standarto gairių. Inokuliatas buvo atskiestas neorganine bandymo terpe, kuri buvo paruošta pagal ISO 14851:2019.

Atrinktos popieriaus kompozitų medžiagos rankiniu būdu buvo supjaustytos į 10x10 mm matmenų bandinius. Kaip etaloninė tyrimų medžiaga buvo naudojama mikrokristalinė celiuliozė. Buvo paruošta po tris visų tirtų medžiagų pakartotinius mėginius (n=3). Detalios substrato ir inokuliato charakteristikos bei apskaičiuota teorinė cheminio deguonies poreikio vertė pateikiama žemiau esančioje **23 lentelėje**.

23 lentelė. Aerobinio skaidumo bandinių charakteristikos ir vertės

	Lakiųjų mežiagų kiekis	**OM / SM**	**Medžia-gos masė**	**Lakių-jų mežiagų masė**	**ChDs**	**Band. terpės tūris**	**Darbi-nis tūris**
Substra-to ID	(g/kg)	(%)	(g/but.)	(g/but.)	mgO_2 /but.	(mL)	(mL)
B15Y	940,77	99,7	1,00	0,94	1065,	200	217
B40	927,09	98,9	1,00	0,93	1076,	200	217
B40Y	932,36	99,6	1,00	0,93	1110,	200	217
Celiuliozė	960,71	99,9	1,00	0,96	1188,	200	217
Inokuliatas							
Kompostas	182,27	38,1	20,00	3,65	-	-	-

Eksperimentuose buvo naudojami 1110 ml tūrio stikliniai indai, kurių viršutinėje dalyje CO_2 absorbcijai buvo integruota atskira talpykla su natrio hidroksido tabletėmis. Siekiant užtikrinti vienodą temperatūros pasiskirstymą ir išvengti anaerobinių sąlygų susidarymo, indai buvo laikomi ant IS 12 indukcinės maišymo sistemos. Pakankamo deguonies kiekio užtikrinimui tyrimo bandinių talpa kas 5–6 dienas buvo aeruojama rankiniu būdu, po 5 minutes. Bandiniai inkubuoti 30 parų, palaikant pastovią 46 °C temperatūrą. Temperatūra buvo parinkta atsižvelgiant į matavimo įrangos specifikacijas (aukščiausia Oxitop sistemos palaikoma temperatūra), pramoninio kompostavimo temperatūros diapozoną[169] bei mikroorganizmų veiklai palankias sąlygas. Pasirinkta temperatūra laikoma pereinamąja – tinkama tiek mezofilinių, tiek termofilinių bakterijų aktyvumui[170], sudaranti optimalią aplinką mikroorganizmų veiklai ir patogenų eliminavimui[171 172].

Aerobinis bandinių medžiagos skaidumas buvo apskaičiuotas pagal matavimo įranga fiksuotas deguonies slėgio pokyčio vertes (hPa/but.). Per visą inkubacijos laikotarpį atlikti 772 matavimai. Duomenys, konvertuoti į Excel formatą, buvo sukelti į kompiuterį ir analizuojami. Respirometre užfiksuotos slėgio matavimų reikšmės konvertuotos į BDS reikšmes naudojant 7 lygtį:

$$\mathrm{BDS} = \frac{M(\mathrm{O_2})}{R \cdot T_m} \left(\frac{V_{\mathrm{tot}} - V_l}{V_l} \right) \alpha \left(\frac{T_m}{T_0} \right) \Delta p(\mathrm{O_2}) \qquad (7)$$

čia:
$M(O_2)$ = Deguonies molekulinė masė (32,000 mg/mol);
R = Dujų konstanta (83.144 L·hPa/(mol·K));
T_0 = Temperatūta (273.15 K);
Tm = Bandinių inkubavimo temperatūra (319.15 K BDS);
Vtot = Butelio tūris [mL];
V1 = Bandinio užimamas tūris [mL];
α = Bunseno absorbcijos koeficientas (0.03103);
$\Delta p(O_2)$ = Dalinio deguonies slėgio skirtumas [hPa].

Medžiagos biologinio skaidumo efektyvumo skaičiavimas buvo patikslintas atsižvelgiant į tai, kad dalis cheminio deguonies suvartojimo (ChDS) tenka ne medžiagos skaidymui, o naujos mikroorganizmų biomasės formavimuisi[173]. Galutinis medžiagos bandinio biologinio skaidumo efektyvumas apskaičiuotas taikant 8 lygtį:

$$\text{Biologinio skaidumo efektyvumas (\%)} = (0.9 \times BDS_{bendras} / ChDs_{bendras}) \times 100 \quad (8)$$

Anaerobinio skaidumo tyrimai

Anaerobiniam tyrimui naudotas inokuliatas – aktyvusis dumblas – prieš bandymą buvo 7 dienas degazuojamas. Vadovaujantis tyrimų laboratorijoje naudojamu Italijos standartu UNI/TS 11703:2018, inokuliatas buvo papildytas maistinėmis medžiagomis ir praskiestas vandeniu. Popieriaus kompozito medžiaga buvo supjaustyta į 10 × 10 mm dydžio bandinius. Mikrokristalinė celiuliozė buvo naudojama kaip etaloninė medžiaga. Paruošta po tris visų bandinių medžiagų pakartotinius mėginius (n=3). Pradiniame bandymo etape bendrųjų kietųjų dalelių koncentracija ir pH reikšmė buvo nustatytos atsižvelgiant į ISO 14853 standarte nurodytus parametrus. Išsami tiriamųjų medžiagų charakteristika pateikiama **24 lentelėje.**

24 lentelė. Anaerobinio skaidumo bandinių charakteristikos ir vertės

	Lakiųjų medž. kiekis	**OM/ SM**	**Medžia-gos masė**	**Lakiųjų medžiagų masė**	**ChDs**	**Van-dens tūris**	**Maist-inių medž. tūris**	**Darbi-nis tūris**
Substrato ID	(g/kg)	(%)	(gFM,S/ but.)	(gVS, S/but.)	mgO_2/ but.)	(mL)	(mL)	(mL)
B15Y	940,77	99,71	2,42	2,28	2572,7	74,80	52,8	480,00
B40	927,09	98,92	2,45	2,27	2625,7	74,80	52,8	480,00
B40Y	932,36	99,62	2,44	2,27	2704,3	74,80	52,8	480,00
Celiuliozė	960,71	99,99	2,39	2,30	2832,2	74,80	52,8	480,00
Inokuliatas								
Aktyvusis dumblas	13,77	57,35	350,00	4,82	-	-	-	-

Anaerobinio skaidumo tyrimai buvo atlikti naudojant „Gas Endeavour III“ (GE III, BPC Instruments, Švedija) sistemą, kurią sudaro 18 vienetų 500 ml talpos reaktorių su dujų srauto matuokliais ir automatine duomenų registravimo sistema. Bandymai buvo vykdomi termofilinėmis sąlygomis – esant 55°C temperatūrai [174] [175] [176]. Bandymo indai buvo inkubuojami 30 dienų[177] [178] užtikrinant nuolatinį maišymą. Anaerobinis medžiagos bandinių skaidumas buvo apskaičiuotas pagal bendrą sugeneruoto metano kiekį (NmL CH_4/butelis) ir taikant normalizuotą metano gamybos ekvivalentą α (0.32 mL CH_4 / 1 mg ChDS[179]) perskaičiuotas į atitinkamas cheminio deguonies suvartojimo (ChDS) reikšmes.

Biologinio medžiagų skaidumo efektyvumas anaerobinėmis sąlygomis buvo apskaičiuotas, lyginant pagaminto metano kiekį su teoriškai apskaičiuotu metano dujų kiekiu pagal formulę 9:

$$\text{Biologinio skaidumo efektyvumas (\%)} = \left(\frac{\mathrm{CH_4\ Sugeneruotas}}{\mathrm{Teorinis\ CH_4}}\right) \times 100 \qquad (9)$$

4.6. Svarbiausi darbo rezultatai

Pakuotės žiedinėje ekonomikoje

Atlikta literatūros apžvalga parodė, kad biologiškai skaidžios pakuotės sprendimai gali būti optimizuojami didinant pakuotės atliekų perdirbamumą, mažinant išteklių suvartojimą ir taip gerinant jų aplinkosauginį efektyvumą. Tikslingas atsinaujinančių žaliavų, pramonės šalutinių gamybos produktų ir biologiškai skaidžių dangų pasirinkimas leidžia užtikrinti pakuotės funkcionalumą, suderinant jį ją su žiedinės ekonomikos principais. Remiantis literatūros analizės duomenimis, buvo išskirti aplinkosauginio veiksmingumo parametrai, kurie buvo taikomi kuriant greitojo maisto pakuotės medžiagas:

Medžiagų perdirbamumo didinimas. Mechaniniu būdu neperdirbamos biologinės kilmės vienkartinės maisto pakuotės gali būti nukreipiamos į biologinio perdirbimo ciklus.

Atsinaujinančių žaliavų naudojimas. Pakuotės gaminamos tik iš atsinaujinančios kilmės žaliavų mažina priklausomybę nuo iškastinio kuro ir neigiamą poveikį aplinkai.

Žaliavų kiekio mažinimas. Pirminių žaliavų poreikį galima sumažinti pakeičiant jas antrinėmis žaliavomis ar / ir šalutiniais gamybos produktais.

Energijos vartojimo mažinimas. Šalutiniai gamybos produktai nereikalauja papildomos energijos jų auginimui ar apdorojimui, todėl juos naudojant kaip žaliavą yra taupomos energetinės sąnaudos.

Cheminių medžiagų kiekio mažinimas. Tinkamai parinkti šalutiniai produktai ar gamybos atliekos gali būti naudojamos chemiškai neapdorotos. Taip sumažinamas cheminių medžiagų kiekis. Pakeičiant konvencinio plastiko dangas biologinės kilmės dangomis nebenaudojamas iškastinis kuras.

Regioninė industrinė simbiozė. Naudojant tame pačiame regione prieinamas žaliavas ir gamybos šalutinius produktus, mažinamas transportavimo poveikis aplinkai, CO_2 emisijos ir didinamas vietinių išteklių panaudojimo efektyvumas.

Baltijos šalių regione prieinamų alternatyvių žaliavų – šalutinių gamybos produktų – analizė parodė, kad kviečių grūdų šalutiniai apdirbimo produktai yra tinkama alternatyva medienos pluoštui. Šioms žaliavoms būdingas didelis lignoceliuliozės kiekis, jos yra lokaliai prieinamos, o jų minimalus papildomo apdorojimo poreikis atitinka tvarių žaliavų atrankos kriterijus pagal žiedinės ekonomikos principus.

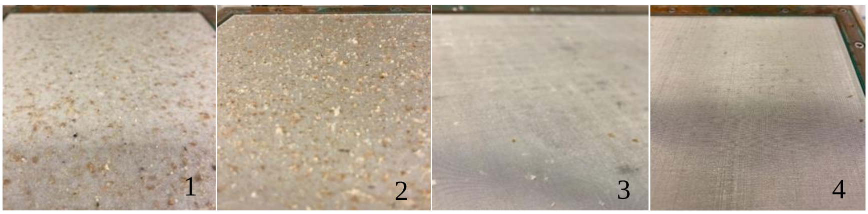
Atlikta biologinės kilmės ir biologiškai skaidžių dangų analizė parodė, kad Saccharomyces cerevisiae – maisto pramonėje plačiai naudojamos mielės – gali būti taikomos kaip funkcinis priedas barjerinėms dangoms formuoti, siekiant pagerinti jų atsparumą drėgmei ir padidinti biologinį skaidumą.

Popieriaus kompozitų gramatūra ir storis

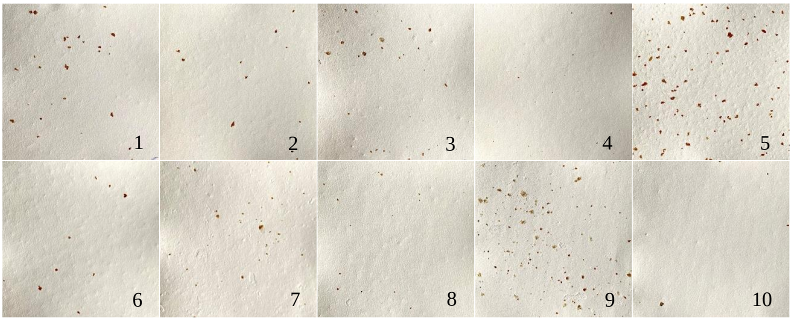
Vertinant sukurtų pakuotės medžiagų bandinių pritaikymą greitojo maisto pakuotėms, išananalizuotos jų bendrosios charakteristikos – gramatūra ir storis – bei galima įtaka fizikinėm-mechaninėms savybėms. Nustatyta, kad užpildų tipas ir koncentracija turėjo reikšmingą poveikį tiek gramatūrai, tiek storio rodikliams.

Gramatūra, apibrėžiama kaip medžiagos masė gramais kvadratiniam metrui (g/m²), tiesiogiai susijusi su popieriaus stiprumu ir patvarumu. CTMP pagrindu sudarytų bandinių gramatūra siekė nuo 64,58 iki 70,05 g/m², o NBSK – nuo 64,10 iki 67,32 g/m². Vidutinis kontrolinių medžiagų storis buvo 121 µm (NBSK) ir 228 µm (CTMP), užpildų įterpimas vidutinį NBSK lakštų storį padidino iki 202 µm, o CTMP – iki 261 µm.

Gramatūros netolygumai siejami su nevienodu užpildų pasiskirstymu popieriaus kompozito matricoje, taip pat neženkliais lakštų pažeidimais džiovinimo metu – nedidelė dalis didesnės frakcijos užpildo dalelių liko prilipusios prie bloterio (žr. **23 ir 24 pav.**). Didžiausias neigiamas poveikis mechaninėms savybėms fiksuotas bandinyje su 40 wt % sėlenų užpildu. Grūdų perdirbimo atliekų užpildas sąlygojo mažesnę savybių variaciją, ypač esant mažesnei (15 wt %) koncentracijai.

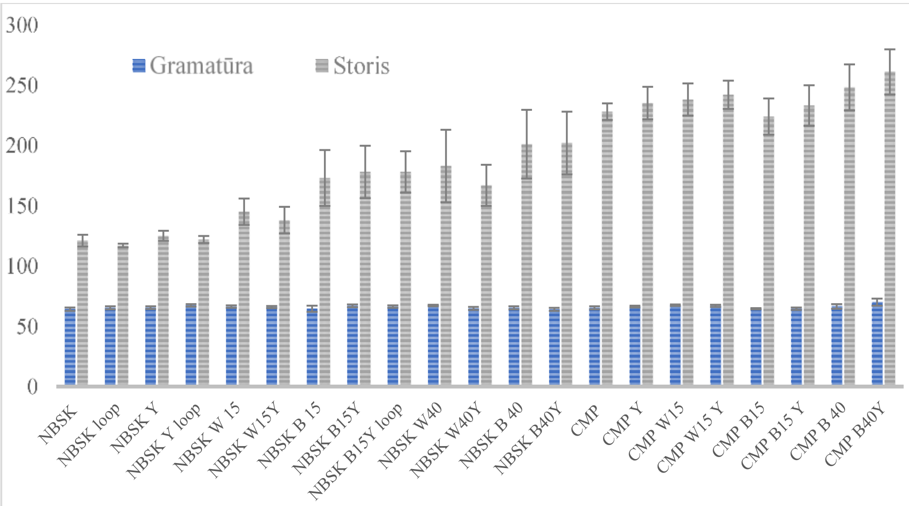


23 pav. 1, 2 – popieriaus lakštas prieš nuimant nuo lakštų formuotuvo. 3, 4 – užpildo dalelės, likusios ant formuotovo nuėmus lakštą



24 pav. Bloteriai po džiovinimo su prilipusiomis užpildų dalelėmis: 1, 2 – 15 wt% kviečių sėlenų bandiniai; 15 wt% kviečių grūdų perdirbimo atliekų bandiniai; 5, 6 – 40 wt% kviečių sėlenų bandiniai; 7, 8 – 40 wt% kviečių grūdų perdirbimo atliekų bandiniai; 9, 10 – CTMP popieriaus lakšto bandiniai su 40 wt% kviečių grūdų perdirbimo atliekų.

CTMP lakštai su 40 wt % kviečių perdirbimo atliekomis buvo pašalinti iš tolimesnių bandymų dėl itin ženklių paviršiaus pažeidimų, atsiradusių po džiovinimo popieriaus bandinius nuimant nuo bloterių. Popieriaus bandinių gramatūros ir storio rezultatų santrauka pateikta **25 paveiksle.**



25 pav. Bandinių gramatūra ir storis

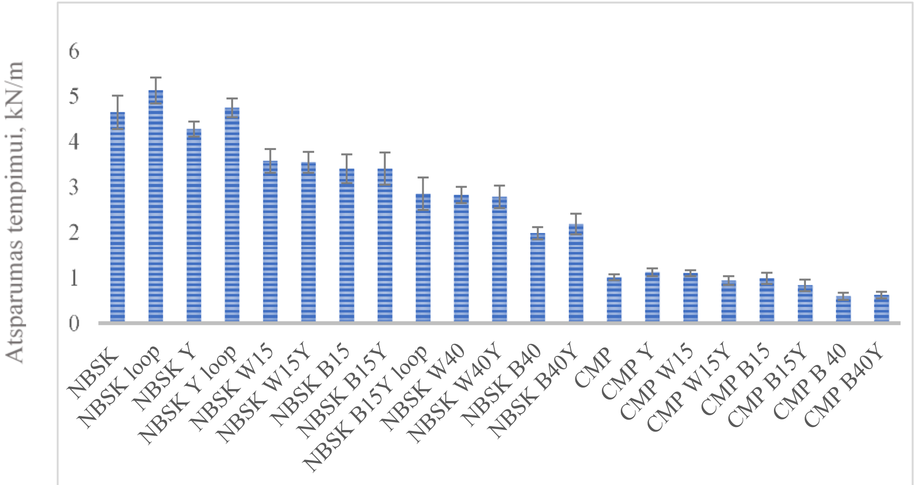
Apibendrinant galima teigti, kad didesnės užpildų koncentracijos lėmė ne tik gramatūros ir storio reikšmių padidėjimą, bet ir didesnę šių parametrų variaciją. Mažesnės frakcijos užpildai turėjo mažesnę įtaką struktūriniam netolygumui, lyginant su didesnės frakcijos sėlenų užpildais.

Atsparumas tempimui

Išanalizavus tempiamojo stiprio rezultatus, nustatyta, kad didesnės užpildų koncentracijos (ypač 40 wt %) reikšmingai mažino popieriaus kompozito mechaninį atsparumą. Tai siejama su pluoštų tarpusavio ryšių sumažėjimu. Didžiausią neigiamą poveikį turėjo sėlenų užpildai. NBSK bandinių su 15 wt % kviečių grūdų perdirbimo atliekomis atsparumas tempimui sumažėjo 24 proc. o su 40 wt % – net 40 porc. %, nuo 4,69 kN/m iki 2,8 kN/m. Sėlenų užpildas turėjo dar didesnį poveikį: tempiamojo stiprio reikšmė sumažėjo 31 proc. (iki 3,2 kN/m) su 15 wt % užpildu ir 55 proc. (iki 2,1 kN/m) su 40 wt % užpildu.

Tipiškai dėl trumpesnių pluoštų[183] [184] ir didesnio lignino kiekio[185] CTMP plaušiena pasižymi mažesnėmis atsparumo tempimui savybėmis, lyginant su NBSK. Nors užpildų įterpimas CTMP atveju tempiamąjį stiprį sumažino, šis poveikis buvo ne toks ryškus, kaip NBSK plaušienoje. Dviejų CTMP bandinių tempiamojo stiprio savybės netgi pagerėjo: CTMP su 15 wt % kviečių grūdų perdirbimo atliekomis būdingas 8,9 proc. padidėjimas, o CTMP su mielėmis – 10 proc. padidėjimas.

Užpildo tipas, dalelių dydis ir jų sąveika su skirtingos kilmės celiuliozės matrica turėjo esminę įtaką popieriaus kompozito tempiamajam stipriui. Nustatyta, kad NBSK pagrindu sudarytų bandinių tempiamasis stipris vidutiniškai sumažėjo apie 38 proc., o CTMP pagrindu – apie 15 proc. Gauti rezultatai patvirtina, kad užpildo frakcija, kiekis ir sąveikos pobūdis su pluošto struktūra yra lemiami veiksniai, darantys įtaką kompozitinės medžiagos stipruminėms savybėms. Pastebėta, kad užpildų įtaka NBSK plaušienoje buvo reikšmingesnė, nes šiai plaušienai būdingas aukštas pradinis tempiamojo stiprio rodiklis, todėl net ir nedidelis tarppluoštinių ryšių sumažėjimas lėmė ženklų mechaninių savybių pablogėjimą. Tuo tarpu CTMP plaušienos pradinis tempiamasis stipris buvo žemesnis, todėl užpildų įtaka – mažesnė, o kai kuriose formulėse net fiksuotas stiprio padidėjimas. Tempiamojo stiprio rezultatai pateikti **26 paveiksle**.



26 pav. Bandinių tempiamasis stipris

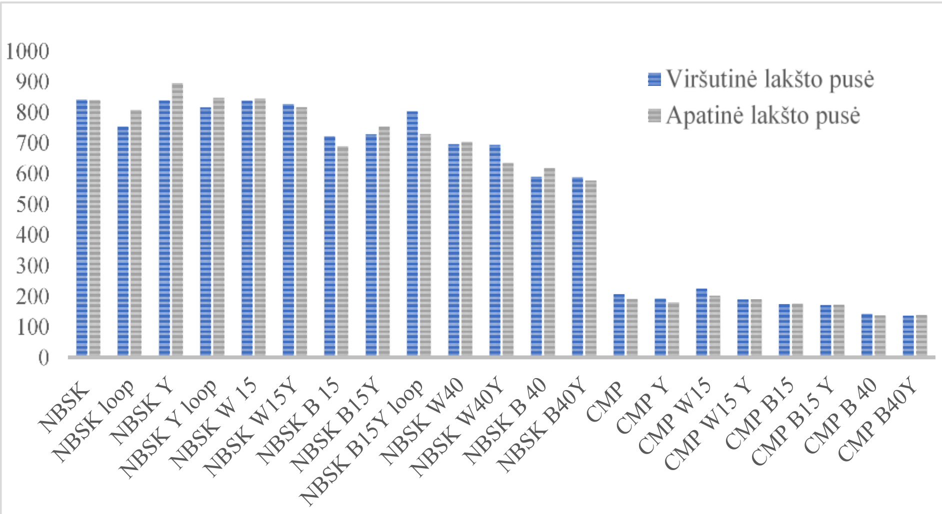
Atsparumas plyšimui

Atsparumas plyšimui glaudžiai susijęs su pluoštų apdirbimu, jų stiprumu, ilgiu ir jų sukibimo savybėmis[187]. Užpildų naudojimas, ypač stambesnių dalelių, mažina pluoštų tinklo integralumą ir sudaro sąlygas lokalizuotų silpnų taškų formavimuisi.

Bandymų rezultatai parodė, kad atsparumas plyšimui mažėjo didinant tiek kviečių grūdų perdirbimo atliekų, tiek kviečių sėlenų užpildų kiekį. Ryškiausias poveikis fiksuotas bandiniuose su 40 wt % sėlenų užpildu – toks užpildo kiekis atsparumą plyšimui sumažino maždaug 30 proc. tiek NBSK, tiek CTMP bandiniuose. Įterpus 15 wt % sėlenų, NBSK lakštų plyšimo atsparumas sumažėjo 14 proc. – nuo 839 mN iki 737 mN, o CTMP – 29 proc., iki 592 mN.

Kviečių grūdų perdirbimo atliekos turėjo mažesnį neigiamą poveikį – esant 15 wt % koncentracijai reikšmingų pokyčių nefiksuota, o 40 wt % užpildas NBSK lakštuose sumažino atsparumą plyšimui 18,8 proc. Tai patvirtina, kad užpildo dalelių dydis ir jų pasiskirstymas pluošto matricoje yra reikšmingi veiksniai – stambesnės sėlenų frakcijos dažniau sutrikdo ryšių struktūrą ir sumažina pluoštų tarpusavio sukibimą.

Mielių priedo įtaka buvo nežymi. Vidutinis atsparumo plyšimui sumažėjimas bandiniuose su mielėmis siekė apie 7 proc., tačiau dviems bandiniams – NBSK be užpildų ir NBSK su 15 wt % sėlenų – buvo būdingas 4 proc. padidėjimas. Tai rodo, kad mielių poveikis gali būti priklausomas nuo užpildo tipo ir visos kompozicinės struktūros. Visi atsparumo plyšimui tyrimų rezultatai pateikti **27 paveiksle**.



27 pav. Bandinių atsparumas plėšimui

Atsparumas lenkimui

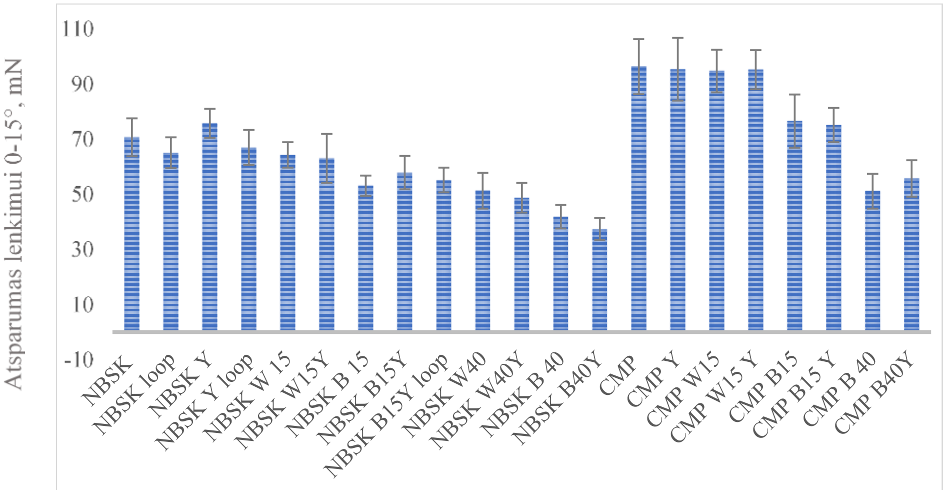
Atsparumas lenkimui apibūdina popieriaus standumą[188] ir jo atsparumą lenkimui, priklausantį nuo medžiagos elastingumo bei jos storio. Ši savybė yra svarbi vertinant pakuotės standumą ir jos gebėjimą apsaugoti turinį nuo mechaninių pažeidimų ir tiesiogiai priklauso nuo popieriaus storio bei gramatūros[190]. Atsparumas lenkimui – tai jėga, reikalinga kartono bandiniui sulenkti 15° kampu, tuo tarpu lenkimo standumas matuojamas esant 5° išlinkiui[191 192].

Kadangi standumas tiesiogiai priklauso nuo storio ir gramatūros, didžiausios atsparumo lenkimui reikšmės buvo nustatytos CTMP bandiniuose, kurių storis siekė 224–261 µm.

Užpildai atsparumą lenkimui sumažino beveik visais atvejais, o pokyčio dydis priklausė nuo užpildo tipo ir koncentracijos. CTMP bandinyje su 15 wt % kviečių grūdų perdirbimo atliekų šio parametro sumažėjimas buvo minimalus – tik 1,3 proc.. Tuo tarpu sėlenų užpildai reikšmingai paveikė struktūrinį vientisumą: 15 wt % ir 40 wt % koncentracijos sumažino atsparumą lenkimui atitinkamai 21,3 proc. ir 44,5 proc.

NBSK bandiniuose kviečių grūdų perdirbimo atliekos sumažino lenkimo atsparumą 9,1 proc. (15 wt %) ir 29 proc. (40 wt %), o sėlenos – 21,4 proc. ir 43,9 proc.

Apibendrinant galima teigti, kad didžiausi pokyčiai fiksuoti naudojant didesnės koncentracijos sėlenų užpildą, mažiausią neigiamą poveikį padarė smulkesnės frakcijos kviečių atliekų užpildas su 15 wt %. Visi rezultatai pateikti **28 paveiksle**.



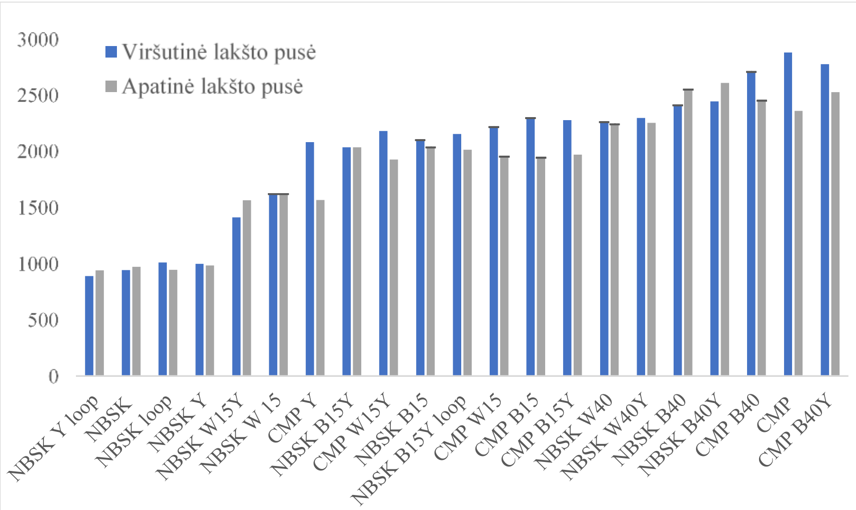
28 pav. Bandinių atsparumas lenkimui

Popieriaus paviršiaus šiurkštumo nustatymas

Paviršiaus šiurkštumas yra itin svarbus parametras popieriui su dangomis, nes jis tiesiogiai veikia dangos technologijos pasirinkimą, dangos medžiagos išeigą ir dangos sukibimą su pagrindu[193]. Lygesnis paviršius leidžia tolygiau paskirstyti dangą, pagerina barjerines savybes ir sumažina medžiagų sąnaudas. Šiurkštumas matuojamas pagal oro tūrį (ml/min), pratekantį tarp matavimo zondų ir paviršiaus – mažesnės reikšmės rodo lygesnį paviršių.

Eksperimentų metu mažiausias paviršiaus šiurkštumas buvo nustatytas NBSK plaušienos mėginiuose be užpildų. Uždaro ciklo formavimo metodu paruoštuose bandiniuose su mielėmis paviršius buvo net 12 proc. lygesnis, palyginti su analogiškais bandiniais be mielių. CTMP lakštuose su 15 wt % sėlenų užpildu fiksuotas 19 proc. paviršiaus lygumo padidėjimas, rodantis, kad smulkesnės frakcijos užpildo dalelės į plaušienos matricą integruojasi tolygiau ir medžiagos paviršių padaro dar lygesnį. Tuo tarpu NBSK bandiniuose su 15 wt % kviečių grūdų perdirbimo atliekų ar sėlenų užpildais paviršiaus šiurkštumas padidėjo atitinkamai 69 proc. ir 116 proc., o su 40 wt % užpildų – 135 proc. ir 159 proc.

Mielių priedas turėjo skirtingą poveikį – kai kuriais atvejais paviršius tapdavo lygesnis, ypač kartu su smulkesnėmis užpildo frakcijomis, tačiau bandiniuose su stambesnėmis užpildų frakcijomis (pvz., sėlenomis) efektas buvo nereikšmingas arba neigiamas. Tai rodo, kad mielių poveikis priklauso nuo jų sąveikos su kitais kompozito komponentais. Visi šiurkštumo bandymo rezultatai pateikti **29 paveiksle**.



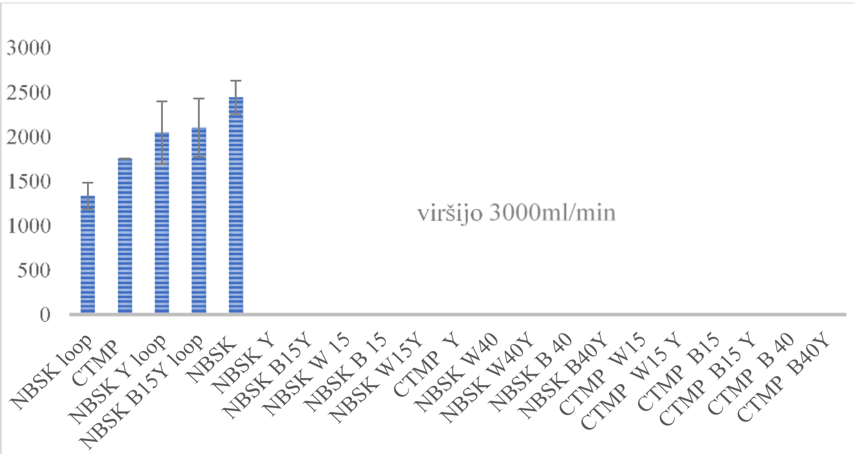
29 pav. Popieriaus paviršiaus šiurkštumas

Pralaidumas orui ir kontaktinio vandens kampo matavimas

Popieriaus barjerinės ir fizikinės-mechaninės savybės yra esminės vertinant medžiagų tinkamumą pakuotėms. Tokie parametrai kaip oro pralaidumas ir hidrofobiškumas leidžia įvertinti medžiagos gebėjimą apsaugoti pakuojamus produktus nuo išorinių veiksnių – drėgmės, oro poveikio – ir padeda tiksliai apibrėžti, kuriam produktų segmentui medžiaga yra tinkamiausia. Greitojo maisto pakuotėms oro pralaidumas nėra kritinis parametras, tačiau pakankamas hidrofobiškumas būtinas siekiant užtikrinti, kad pakuotė eksploatacijos metu nepraleistų skysčių.

Dėl celiuliozės pluoštų poringumo popieriaus medžiagos paprastai pasižymi prastomis deguonies ir skysčių pralaidumo barjerinėmis savybėmis[195]. Atliekant oro pralaidumo tyrimus, nustatyta, kad visų CTMP ir NBSK lakštų su užpildais oro pralaidumas viršijo 3000 ml/min ribinę matavimų vertę, todėl šie rezultatai **30 pav.** neatvaizduoti.

Mažiausias oro pralaidumas (1752 ml/min) nustatytas NBSK plaušienos bandinyje be priedų, pagamintame uždaro ciklo formavimo metodu. Lyginant su standartiniu lakštų formavimo būdu, šis metodas leido sumažinti oro pralaidumą net 45 proc., tikėtina dėl cikle recirkuliuojančių mikro- ir nanodalelių, kurios sumažino medžiagos poringumą. Pridėjus mielių priedą, oro pralaidumas padidėjo 50,8 proc. CTMP bandiniuose (iki 3561 ml/min) ir 24 proc. NBSK bandiniuose (iki 3216 ml/min). Bandiniuose su užpildais mielės neturėjo statistiškai reikšmingo poveikio, nes visi mėginiai viršijo 3000 ml/min. Dėl užpildų, ypač stambesnių frakcijų, netolygaus pasiskirstymo plaušienos matricoje tarp pluoštų gali susidaryti tuščios zonos, kurios sumažina medžiagos struktūrinį vientisumą ir padidina oro pralaidumą. Oro pralaidumo matavimų duomenys pateikti **30 pav.**

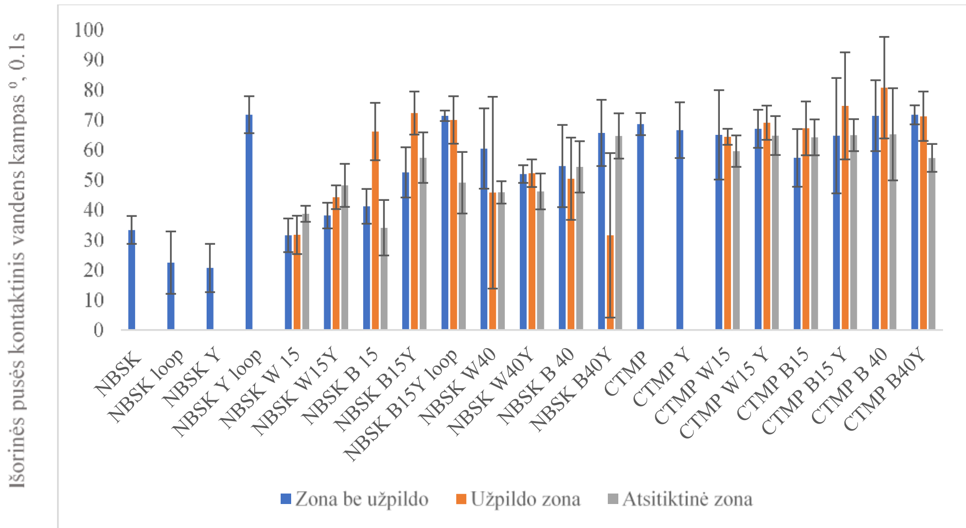


30 pav. Popieriaus pralaidumas orui

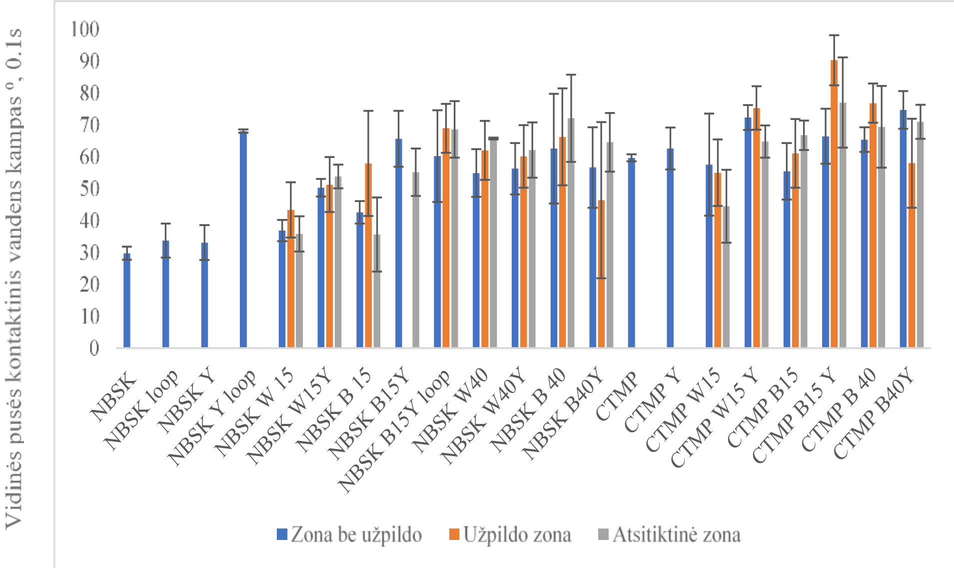
Kontaktinio kampo matavimai atlikti siekiant įvertinti popieriaus kompozito paviršiaus hidrofobiškumą – vieną iš esminių barjerinių savybių, lemiančių pakuotės tinkamumą sąlyčiui su skysčiais. Ši savybė ypač svarbi greitojo maisto pakuotėms, kurios turi užtikrinti trumpalaikę apsaugą nuo drėgmės ir riebalų, neprarasdamos mechaninio vientisumo. Kontaktinis kampas apibūdina skysčio sąveiką su matuojamos medžiagos paviršiumi, t. y. kaip vandens lašas pasiskirsto ar įsigeria[196]. Hidrofobiškumo laipsnis nusakomas kontaktiniu kampu: kampas >90° rodo hidrofobišką (atsparų vandeniui) paviršių, o 0° žymi visišką medžiagos hidrofiliškumą.

Didžiausios kontaktinio kampo vidutinės reikšmės (73°), užfiksuotos CTMP B15Y bandinyje ir CTMP bandinyje su 40 wt % sėlenų užpildu, siekė 71°. Didžiausia pavienė kontaktinio kampo reikšmė (90°) nustatyta CTMP B15Y bandinyje, užpildo zonoje, vidinėje lakšto pusėje. Vandens lašas pro stambią sėlenų frakciją neprasiskverbė, tai parodo itin stiprią lokalią hidrofobiškumo savybę. Aukščiausia kontaktinio kampo vertė NBSK plaušienos bandiniuose su užpildais buvo užfiksuota bandinyje su 40 wt % kviečių grūdų perdirbimo atliekų – kontaktinis kampas siekė 64°. NBSK su 15 wt % sėlenų užpildu – apie 56° (vidutinė reikšmė). Bandiniuose be užpildų naudojant uždaro ciklo formavimo metodą bei mielių priedą nustatytas 72° kontaktinis kampas, tuo tarpu analogiškame bandinyje be mielių kontaktinis kampas siekė tik 22°. Tai patvirtina mielių ir smulkiųjų celiuliozės pluoštų sąveiką, kuri gali pagerinti paviršiaus hidrofobiškumą.

Reikšmingi kontaktinio kampo skirtumai tarp lakštų pusių pastebėti tik NBSK bandiniuose be užpildų – vidinė pusė, esant sąlyčiui su formavimo tinkleliu, buvo hidrofobiškesnė. Tai galima paaiškinti tuo, kad tinklelio pusė paprastai pasižymi lygesniu mažiau porėtu paviršiumi, susidaro mažiau šiurkštumo netolygumų. **31 ir 32 paveiksluose** yra pateikiami išsamūs kontaktinio kampo matavimai tiek išorinėje, tiek vidinėje lakšto pusėje bei visose trijose skirtingose matavimų zonose – zonoje be užpildo, užpildo zonoje ir atsitiktinėje matavimo zonoje.



31 pav. Kontaktinis vandens kampas išorinėje bandinių pusėje, 0.1s.



32 pav. Kontaktinis vandens kampas vidinėje bandinių pusėje 0.1s.

Susisteminti antrame tyrimų etape atliktų fizikinių-mechaninių bei barjerinių savybių tyrimų rezultatai pateikiami žemiau esančioje **25 lentelėje**. Rausvas fonas indikuoja pablogėjusias, o žalsvas fonas – pagerėjusias bandinio savybes.

25 lentelė. Antrojo tyrimų etapo ir rinkoje naudojamo popieriaus parametrai

Bandinys	**Bendrosios charakteristikos**		**Fizikinės-mechaninės savybės**				**Barjerinės savybės**	
	Gram-atūra, g/m²	**Storis, µm**	**Tempi-mo stipris, kN/m**	**Trūkio defor-macija, %**	**Atspa-rumas plyšiui, MN**	**Lekim. atspar umas, mN**	**Oro pralai dum., ml/min**	**Kont akt. kam pas, °**
CTMP (kontrol. bandinys)	65,33	228	1,01	1,38	199	96,30	1752	64,10
CTMP B15	64,63	224	0,99	0,96	175	76,50	virš.	61,94
CTMP B15Y	64,58	233	0,83	0,86	172	75,10	virš.	72,94
CTMP B40	66,50	248	0,59	0,76	140	51,10	virš.	71,42
CTMP B40Y	70,05	261	0,62	0,81	137	55,70	virš.	67,25
CTMP W15	67,42	238	1,10	1,17	213	94,70	virš.	57,62
CTMP W15Y	66,88	242	0,94	1,04	189	95,20	virš.	68,80
CTMP Y	66,38	235	1,12	1,25	186	95,30	virš.	64,53

NBSK (kontrol. bandinys)	64,30	121	4,64	3,95	839	70,60	2441	31,50
NBSK B15	64,58	173	3,40	2,88	705	53,10	virš.	46,20
NBSK B15Y	67,05	178	3,40	2,89	740	57,80	virš.	50,45
NBSK B15Y uždaro ciklo metodas	66,30	178	2,85	2,47	765	55,10	2100	64,63
NBSK B40	65,33	201	1,98	2,02	603	41,80	virš.	59,99
NBSK B40Y	64,10	202	2,18	2,30	582	37,30	virš.	54,85
NBSK uždaro ciklo metodas	65,40	117	5,12	4,37	780	65,00	1334	28,04
NBSK W15	66,35	145	3,57	3,72	841	64,20	virš.	36,30
NBSK W15Y	66,00	138	3,54	3,72	821	63,00	virš.	47,61
NBSK W40	67,32	183	2,82	3,40	699	51,30	virš.	55,74
NBSK W40Y	64,88	167	2,78	3,24	664	48,70	virš.	54,76
NBSK Y	65,50	125	4,27	4,06	866	75,70	virš.	26,83
NBSK Y uždaro ciklo metodas	67,30	122	4,74	4,12	830	66,90	2046	69,85
Greitojo maisto pakuočių pvz.	75–325	100–650	MD: 7,9–15,6 CD: 4,5–8,5	-	MD: 950–1830 CD: 1000–2100	MD: 125–415 CD: 65–250	-	74,2–82,7

Greitojo maisto pakuotės yra skirtos trumpalaikiam naudojimui, o jose esantis produkto svoris nėra didelis, todėl tokios pakuotės neturi pasižymėti itin dideliu medžiagos atsparumu tempimui ar plėšimui. Esminė jų funkcija trumpuoju laikotarpiu – užtikrinti tinkamas hidrofobiškumo savybes ir pakankamą medžiagos standumą, o po vartojimo – lengvą atliekų tvarkymą. Lyginant laboratorinėmis sąlygomis pagamintų kompozitinių lakštų ir pramoniniu būdu iš analogiškų žaliavų gaminamų medžiagų fizikines-mechanines savybes, tikėtina, kad vykdant pramoninius procesus būtų pasiekti geresni rezultatai dėl kelių priežasčių:

Didesnė gramatūra: laboratorinių lakštų gramatūra buvo parinkta vadovaujantis ISO 5269-1:2005 standartu, kuriame nurodoma siektina 60 g/m² vertė. Tuo tarpu atsižvelgiant į konkrečius funkcinius reikalavimus pramonėje naudojamų greitojo maisto pakuočių gramatūra būna ženkliai didesnė. Didesnė gramatūra siejama su didesniu pluošto tankiu, todėl susidaro stipresni tarppluoštiniai ryšiai, didinantys tempiamąjį stiprį. Be to, tokie lakštai dažnai būna elastingesni ir atsparesni plyšimui, ypač skersine (CD) kryptimi.

Pluošto orientacija: pramoninėmis sąlygomis pagaminamo popieriaus plaušų orientacija yra kontroliuojama mašinine kryptimi (MD) ir skersine kryptimi (CD), taip optimizuojant medžiagos stiprumą. Tikslinė plaušų orientacija pagerina medžiagos gebėjimą paskirstyti įtempius, todėl pagerėja medžiagos savybės. Laboratorijoje rankiniu būdu gaminami lakštai pasižymi atsitiktiniu plaušų išsidėstymu, o tai reiškia, kad medžiaga nepasižymi atitinkamai krypčiai būdingomis stiprumo savybėmis. Todėl atsparumas tempimui ir atsparumas plyšimui yra vienodi visomis kryptimis ir yra mažesni, nei pramoniniu būdu gaminamų lakštų.

Pramoniniai apdorojimo būdai: pramoninis presavimas padidina pluošto tankį, kuris tiesiogiai padidina tempimo stiprį ir medžiagos standumą, užtikrina vienodesnę medžiagos struktūrą, o tai tiesiogiai daro įtaką fizikinėms-mechaninėms bei barjerinėms savybėms.

Nors laboratoriniuose kompozitų lakštuose oro pralaidumas (lyginant su homogeniškais kontroliniais lakštais) sumažėjo, šis parametras greitojo maisto pakuotėms nėra esminis. Kur kas svarbesnis – medžiagos hidrofobiškumas, t. y. atsparumas drėgmei ar riebalams, nes šio tipo produktuose dažnai yra skystų komponentų (pvz., padažų ar užpilų), kurie gali prasiskverbti per pakuotės medžiagą. Todėl būtina, kad medžiaga trumpą laiką išlaikytų vientisą struktūrą ir nepraleistų skysčių.

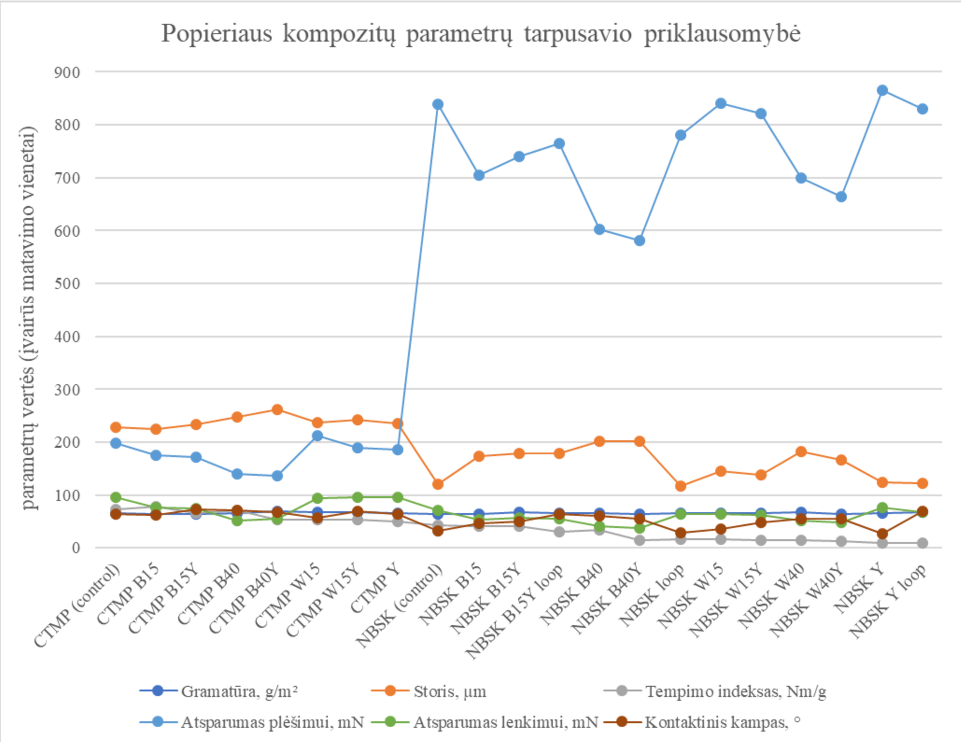
33 pav. pateikiama kompleksinė kviečių sėlenų ir grūdų perdirbimo šalutinių produktų užpildų poveikio pagrindiniams popieriaus kompozitų parametrams bei jų tarpusavio priklausomybių analizė.

Gramatūros ir storio priklausomybė. Tarp gramatūros ir storio fiksuotas teigiamas parametrų priklausomybės ryšys – didėjant užpildo kiekiui, didėja lakšto gramatūra ir svoris. Ši priklausomybė ypač aiški CTMP B40Y mėginyje, kurio gramatūra siekė 70,05 g/m², o storis – net 261 µm, lyginant su CTMP kontroliniu bandiniu (65,33 g/m², 228 µm). Panašus santykis pastebimas ir lyginant NBSK B40 (65,33 g/m², 201 µm) su kontroliniu bandiniu (64,3 g/m², 121 µm).

Storio ir tempiamojo stiprio priklausomybė. Paprastai didesnis storis turėtų lemti aukštesnį tempiamąjį stiprį, tačiau užpildai šią priklausomybę silpnina. Užpildų dalelės sutrikdo pluoštų tarpusavio sąveiką ir riboja stiprių vandenilinių ryšių susidarymą, dėl to, nepaisant didesnio storio, tempiamasis stipris sumažėja.

Tempiamojo stiprio ir atsparumo plyšimui priklausomybė. Tarp šių dviejų parametrų taip pat matoma teigiamas priklausomybės ryšys – mažėjant tempiamajam stipriui, reikšmingai sumažėja ir atsparumas plyšimui. Pvz., CTMP kontroliniam mėginiui būdingas 199 mN atsparumas plyšimui, o CTMP B40Y – tik

137 mN. NBSK kontrolinio bandinio atsparumas plėšimui siekė 839 mN, o NBSK B40Y – 582 mN.



33 pav. Popieriaus kompozitų fizikinių-mechaninių parametrų priklausomybė ryšiai

Atsparumas lenkimui didinant užpildų kiekį mažėja. Nors šalutinių grūdų apdirbimo užpildas kai kuriais atvejais leido geriau išlaikyti standumą nei sėlenų užpildai, bendros tendencijos rodo, kad didesnė užpildų koncentracija lemia ryškų medžiagos standumo sumažėjimą, kurį sąlygoja silpnesnės pluoštų sąveikos ir sumažėjęs pluoštų tinklo integralumas.

Kontaktinis kampas. Skirtingai nei fizikinių-mechaninių savybių parametrai, kontaktinio kampo reikšmės su užpildais padidėjo. Pastebėtas teigiamas parametrų priklausomybės ryšys tarp medžiagos storio ir kontaktinio kampo – storesni lakštai su užpildais tapo hidrofobiškesni.

Apibendrinant galima teigti, kad **33 pav**. aiškiai iliustruoja, jog kviečių sėlenų ir šalutiniai grūdų apdirbimo užpildai turi kompleksinį poveikį popieriaus kompozitų savybėms – gerinamos barjerinės (hidrofobiškumo) savybės, tačiau silpninamos fizikinės-mechaninės charakteristikos. Tai svarbu atsižvelgiant į galutinį pakuotės taikymą ir eksploatacinius poreikius.

Geriausiomis hidrofobiškumo savybėmis pasižymėję, geresnių mechaninių parametrų NBSK plaušienos kompozitai – NBSK B15Y ir NBSK B40 – buvo atrinkti tolesniam biologinio skaidumo tyrimų etapui.

Aerobinis medžiagos skaidumas

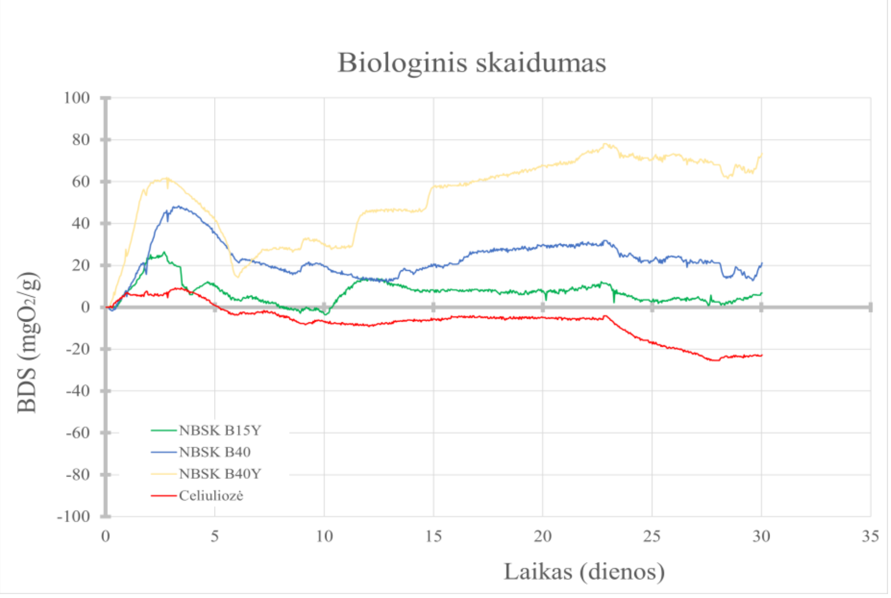
Geriausiomis hidrofobiškumo savybėmis pasižymėję, geresnių mechaninių parametrų NBSK plaušienos kompozitai – NBSK B15Y ir NBSK B40 – buvo atrinkti tolesniam biologinio skaidumo tyrimų etapui.

26 lentelėje pateikiami aerobinio biologinio skaidumo tyrimų rezultatai. Lentelėje nurodomas apskaičiuotas teorinis cheminio deguonies suvartojimo poreikis (ChDs, mgO_2/L), realus deguonies suvartojimas per inkubacijos laikotarpį bei patikslintas ChDs, įvertinant 10 proc. deguonies dalį, sunaudotą naujai mikroorganizmų biomasei susidaryti. Taip pat pateikiamas apskaičiuotas biologinio skaidumo efektyvumas (proc. %).

26 lentelė. Aerobinio medžiagos skaidumo bandymo duomenys

Substrato ID	**Pradinis teorinis ChDs (mgO_2/L)**	**Gautas ChDs poreikis (mgO_2/L)**	**VK (proc.)**	**Patikslintas ChDs (mgO_2/L)**	**Biologinio skaidumo efektyvumas (proc.)**
B15Y	4910,7	122,4	7,1	110,2	2,2
B40	4962,9	224,2	5,7	201,8	4,1
B40Y	5117,1	360,7	3,8	324,6	6,3
Celiuliozė	5475,6	43,0	17,3	38,7	0,7

34 paveiksle pavaizduota 30 dienų BDS kreivė.



34 pav. Anaerobinio skaidumo BDS (mgO2/g) 30 dienų kreivė

Etaloniniame bandinyje su celiulioze (raudona linija) fiksuotas nedidelis deguonies suvartojimas, kuris rodo žemą aerobinio skaidumo lygį – per 30 dienų suskaidyta tik 0,7 proc. medžiagos. Be to, buvo užfiksuotos neigiamos BOD vertės, kurios gali pasitaikyti[202], tačiau tipiškai tokiems tyrimams nėra būdingos. Tokie rezultatai gali reikšti metodologinius netikslumus ar nepakankamą inokuliato neveiksmingumą. Svarbu atkreipti dėmesį į galimas metodines paklaidas, susijusias su matavimo sistema. „Oxitop“ sistema deguonies suvartojimą nustato pagal slėgio pokyčius, o kadangi bandymo buteliukai kas penkias dienas buvo rankiniu būdu atidaromi aeracijai, tai sukėlė didelius slėgio svyravimus ir galėjo turėti įtakos matavimų tikslumui. Be to, bandymo sistemoje CO_2 absorbcijai buvo naudojamas natrio hidroksidas (NaOH), todėl galimi CO_2 absorbcijos intensyvumo svyravimai taip pat galėjo sukelti neįprastai mažas arba net neigiamas BOD reikšmes.

Gauti rezultatai rodo, kad panaudotas inokuliatas ar / ir bandymo sąlygos buvo nepakankamos optimaliam aerobiniam skaidumui, todėl šių bandymų rezultatai negali būti vertinami kaip visiškai patikimi.

Visgi rezultatai rodo, kad bandiniai su kviečių sėlenų užpildu pasižymėjo didesniu biologiniu deguonies suvartojimu ir aukštesniu biologinio skaidumo efektyvumu. Tai gali būti paaiškinama palankesnėmis anaerobinės mikrobiologinės aplinkos sąlygomis, kurias sudarė sėlenose esantys polisacharidai, veikiantys kaip papildomi mitybiniai substratai mikroorganizmams[197].

Bandinys su 15 wt % kviečių sėlenų užpildu pasižymėjo žemiausiu biologinio deguonies poreikiu (ChDs) ir lyginant su kitais bandiniais pasiekė 2,2 proc. biologinio skaidumo efektyvumą, tuo tarpu bandiniui su 40 wt % sėlenų užpildu būdingas aukštesnis 4 proc. biologinio skaidumo efektyvumas. Tai rodo, kad didesnė sėlenų koncentracija skatina efektyvesnį medžiagos skaidumą, kuris tikėtina pasiektas dėl didesnio kiekio mikroorganizmams prieinamų maistinių medžiagų ir struktūrinių polisacharidų[198 199].

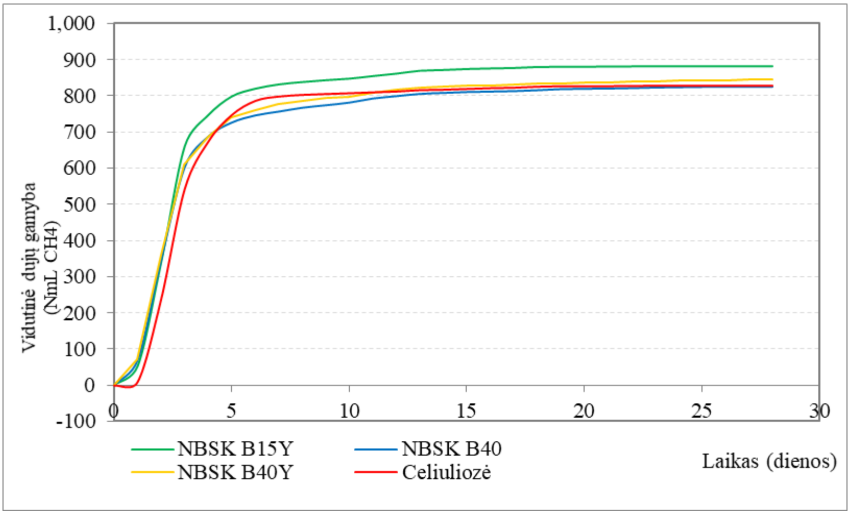
Mielių priedo įterpimas dar labiau pagerino skaidumo rodiklius – bandinyje B40Y (40 wt % sėlenų su mielėmis) biologinis skaidumo efektyvumas pasiekė 6,3 proc.. Tai gali būti pagrindžiama *Saccharomyces cerevisiae* mielių sudėtimi – jų biomasė gausi baltymų, vitaminų ir mineralų, kurie skatina mikroorganizmų augimą ir aktyvumą[200]. Be to, mielių ląstelės gali veikti kaip matrica, tinkama mikroorganizmų kolonizacijai[221].

Anaerobinis medžiagos skaidumas

27 lentelėje pateikti anaerobinio biologinio skaidymo (BMP) bandymų rezultatai. Nurodomi pagrindiniai parametrai: apskaičiuotas pradinis teorinis cheminio deguonies poreikis (ChDs), sugeneruotas ir galutinis metano (CH_4) kiekis, apskaičiuota teorinė metano gamybos vertė ir biologinio skaidumo efektyvumas, o diagramoje (**35 pav.**) vaizduojama (NmL CH_4) 30 d. gamybos kreivė.

27 lentelė. Anaerobinio medžiagos skaidumo bandymo duomenys

Substrato ID	**Pradinis ChDs (mgO_2/L**	**Sugeneruotas CH_4 (mL/L)**	**VK (proc.%)**	**Galutinis CH_4 (mL/L)**	**Teorinis CH_4 (mL/L)**	**Biologinio skaidumo efektyvumas (proc.%)**
B15Y	5358,3	1840,8	2,3	1656,8	1714,7	96,6
B40	5470,8	1721,5	1,4	1549,3	1750,7	88,5
B40Y	5633,3	1765,4	1,7	1588,9	1802,7	88,1
Celiuliozė	5900,0	1726,9	16,7	1554,2	1888,0	82,3



35 pav. 30 dienų vidutinės metano dujų gamybos vertės (NmL CH_4)

Visi mėginiai pasižymėjo aukštais dujų gamybos rodikliais per pirmąsias 5 dienas, po kurių ėjo stabilizacijos fazė. Bandinys su 15 proc. sėlenų užpildu ir mielių priedu pasiekė didžiausias dujų gamybos vertes (883,60 NmL CH_4). Bandinyje su 40 proc. sėlenų užpildu ir mielių priedu fiksuoti šiek tiek mažesni dujų gamybos rodikliai, kuriais remiantis galima daryti išvadą, jog didesnis sėlenų užpildo kiekis sumažina biologinį medžiagos skaidymo efektyvumą. Tai gali sąlygoti tokie veiksniai, kaip lignino, kuris yra atsparus anaerobiniam skaidymui, kiekis[146 147 148 149]. Kitas veiksnys yra mikrobiologinė sinergija. Biologinis skaidumas priklauso nuo sąveikos tarp mikroorganizmų bendruomenių (bakterijų, archėjų ir grybų)[151 152 153].

Visų medžiagos bandinių dujų gamybos kreivė pasižymėjo intensyviu 5 dienų pradiniu etapu, po kurio ėjo stabilizacijos fazė. Didžiausias metano kiekis (883,6 NmL CH_4) užfiksuotas B15Y mėginyje su 15 proc. kviečių sėlenų ir mielių priedu. Šiek tiek mažesnė gamyba (847,4 NmL CH_4) stebėta B40Y mėginyje (40 proc. sėlenų su mielėmis). Tai leidžia daryti prielaidą, jog didesnė sėlenų koncentracija gali apsunkinti anaerobinį skaidymą dėl tokių veiksnių kaip didesnis lignino kiekis, kuris yra sunkiai skaidomas anaerobinėmis sąlygomis[203] [204] [205] [206], bei mikrobiologinė sinergija. Efektyvus biologinis skaidymas priklauso nuo įvairių mikroorganizmų (bakterijų, archėjų ir grybų) ir jų tarpusavio sąveikos, [208] [209] [210] o anaerobinėmis sąlygomis veikiančių mikroorganizmų, galinčių efektyviai skaidyti ligniną, yra labai nedaug[207]. Tai yra viena iš pagrindinių priežasčių, kodėl ligninas laikomas itin atspariu anaerobiniam skaidymui.

Nors 40 proc. sėlenų koncentracija sumažino dujų kiekio išsiskyrimą lyginant su 15 proc., tiek B40, tiek B40Y bandinių rodikliai lyginant su etaloniniu celiuliozės bandiniu buvo aukštesni. Įdomu tai, kad B40Y mėginio galutinis biologinio skaidumo efektyvumas (88,1 proc.) buvo šiek tiek mažesnis nei B40 (88,5 proc.). Tai gali būti paaiškinama pradiniu intensyviu mikroorganizmų aktyvumu – mielių priedas galėjo sukelti greitą pradinę skaidymo fazę, kurios metu buvo sunaudoti lengvai skaidomi komponentai (cukrūs, baltymai), o vėlesniu laikotarpiu substrato likučiai galėjo būti sunkiau skaidomi, ypač dėl skaidymui atsparaus lignino.

Atlikti tyrimai parodė, kad popieriaus kompozitai su kviečių sėlenomis, ypač papildyti mielėmis, pasižymi geresniu biologiniu skaidumu nei grynos celiuliozės bandiniai. Šiuos rezultatus patvirtina ir kiti tyrimai, kurie parodė, kad kviečių sėlenos ir kiti grūdų šalutiniai produktai turi teigiamos įtakos biologiniam skaidumui [211] [212] [213].

4.7. Gautų rezultatų apibendrinimas

Kviečių sėlenų, grūdų apdirbimo šalutinių produktų bei *Saccharomyces cerevisiae* įterpimas į popieriaus pagrindu sukurtus medžiagų kompozitus atskleidė daugialypę sąveiką tarp fizikinių-mechaninių savybių, medžiagos hidrofobiškumo, biologinio skaidumo bei aplinkosauginio efektyvumo.

Didėjant užpildų koncentracijai, pastebimas mechaninių savybių sumažėjimas – tempiamasis stipris, atsparumas plyšimui ir medžiagos standumas lyginant su kontroliniais bandiniais pablogėjo. Nors šie pokyčiai gali riboti tokių medžiagų pritaikymą pakuotėse, kurioms yra būtinas didesnis mechaninis atsparumas, tačiau vienkartinėms greitojo maisto pakuotėms, kuriose yra aktualus medžiagos hidrofobiškumas, toks fizikinių-mechaninių savybių sumažėjimas nėra esminis trūkumas. Kalbant apie tokio tipo pakuočių medžiagas, pirmenybė teikiama gebėjimui atlaikyti trumpalaikį kontaktą su maistu ir skysčiais, užtikrinti patogų vartojimą ir palengvinti atliekų tvarkymą gyvavimo ciklo pabaigoje.

Saccharomyces cerevisiae priedas taip pat modifikavo medžiagų fizines ir funkcines savybes. Viena iš reikšmingiausių naudų, susijusių su didesne užpildų koncentracija ir mielių užpildu – padidėjęs hidrofobiškumas. Medžiagos kompozitai pasižymėjo didesniu atsparumu vandeniui – tai itin svarbi savybė maisto pakuotėms, kuriose siekiama pakeisti įprastas plastiko dangas biopagrindu pagamintais sprendimais, kurie leidžia sumažinti priklausomybę nuo iškastinio plastiko, mažina mikroplastiko taršos riziką.

Užpildai ir *Saccharomyces cerevisiae* priedas turėjo įtakos medžiagų biologinio skaidumo efektyvumui. Aplinkosauginiu požiūriu tokia medžiagos sudėtis leidžia užtikrinti ne tik spartesnį medžiagų skaidumą, bet ir jų sėkmingą įtraukimą į biologinio perdirbimo ciklus, mažinant susidarančių atliekų kiekį. Tokios medžiagos yra tinkamos kompostavimui, kuris atitinka žiedinės ekonomikos principus ir įgalina organinių žaliavų grąžinimą atgal į ekosistemą.

Aplinkosauginiu požiūriu didesnės užpildų koncentracijos ir *Saccharomyces cerevisiae* derinys padidina bendrą aplinkosauginį medžiagos efektyvumą. Vienas svarbiausių privalumų – sumažėjęs poreikis naudoti pirmines žaliavas, kadangi žemės ūkio ir pramonės šalutiniai produktai pakeičia dalį pirminių celiuliozės pluoštų. Tai atitinka žiedinės ekonomikos ir pramoninės simbiozės principus, mažina žaliavų eksploatavimą ir su tuo susijusį poveikį aplinkai. Be to, šie šalutiniai produktai yra lengvai prieinami regioniniu mastu, todėl jų naudojimas prisideda prie vietinių tiekimo grandinių stiprinimo ir transportavimo kaštų bei su tuo susijusių emisijų mažinimo. Dar daugiau – šie užpildai nereikalauja intensyvaus auginimo ar papildomo apdorojimo, todėl jų panaudojimas popieriaus kompozituose prisideda prie bendrosios energijos ir cheminių medžiagų suvartojimo.

4.8. Išvados ir rekomendacijos

Išvados

1. Nustatyti vienkartinio greitojo maisto pakuočių aplinkosauginio veiksmingumo kriterijai apima: pirminių žaliavų vartojimo mažinimą, energijos sąnaudų mažinimą, medžiagos perdirbamumą, perėjimą prie atsinaujinančių žaliavų, mažesnį cheminių medžiagų naudojimą bei regioninės pramoninės simbiozės principo įgyvendinimą. Kaip alternatyvios pirminės medienos plaušienos medžiagos, mažinančios pirminių išteklių poreikį ir palaikančios žiedinius medžiagų srautus, identifikuotos kviečių sėlenos ir kviečių grūdų šalutiniai gamybos produktai. Nustatyta, kad *Saccharomyces cerevisiae* potencialiai gali pagerinti medžiagų barjerines savybes ir padidinti biologinio skaidumo efektyvumą, ir tokiu būdu medžiagą efektyviai integruoti į biologinio perdirbimo procesus.
2. Sukurtas biologiškai skaidžios pakuotės medžiagos prototipas, kurio sudėtyje dalis pirminės medienos plaušienos buvo pakeista kviečių sėlenomis ir šalutiniais kviečių apdirbimo produktais. Eksperimentiniai tyrimai parodė, kad iki 40 proc. pirminių žaliavų gali būti pakeista šiais alternatyviais užpildais, išlaikant tinkamas medžiagos funkcines charakteristikas. *Saccharomyces cerevisiae* padidino medžiagos hidrofobiškumą, o tai rodo šio priedo potencialą būti naudojamam biologinės kilmės barjerinėse dangose.
3. Užpildų kiekis padarė neigiamą poveikį medžiagos mechaninėms savybėms: vidutiniškai bendrasis tempiamasis stipris vidutiniškai sumažėjo 19,8 proc., atsparumas plyšimui – 12,3 proc., o atsparumas lenkimui – 19,6 proc.. CTMP kompozituose tempiamasis stipris vidutiniškai sumažėjo 11,88 proc., atsparumas plyšimui – 12,35 proc., o stsparumas lenkimui – 19,10 proc., palyginti su kontroliniais CTMP mėginiais. NBSK pagrindo bandiniuose pokyčiai buvo ryškesni: tempiamasis stipris sumažėjo 30,82 proc., atsparumas plyšimui – 15,61 proc., o atsparumas lenkimui – 25,74 proc..

4. Nepaisant pablogėjusių mechaninių savybių, aštuoni mėginiai su užpildais atitiko funkcinius greitojo maisto pakuočių reikalavimus. *Saccharomyces cerevisiae* priedas padidino medžiagos hidrofobiškumą vidutiniškai 11,95 proc. nesukeldamas reikšmingo pokyčio fizikinėms-mechaninėms savybėms. Užpildai ir mielės pagerino biologinį skaidumą, ypač aerobinėmis sąlygomis, kur didžiausias biologinio skaidumo efektyvumas (183,04 proc.) pasiektas naudojant 40 proc. kviečių sėlenų užpildą su mielių priedu. Aerobinio skaidumo efektyvumas vidutiniškai padidėjo 55,77 proc. Anaerobinėmis sąlygomis didžiausias efektyvumo rodiklis (96,62 proc.) pasiektas mėginiuose su 15 proc. sėlenų ir mielių priedu, o bendras anaerobinio skaidumo efektyvumas padidėjo 12,44 proc. Gauti rezultatai patvirtina, kad sukurta medžiaga potencialiai atitinka funkcinius greitojo maisto pakuočių parametrus ir yra tinkama biologiniam perdirbimui.
5. Gauti rezultatai patvirtina, kad sukurta vienkartinė greitojo maisto pakuotės medžiaga integruoja funkcinius parametrus, biologinį skaidumą ir aplinkosauginį efektyvumą, atitinka žiedinės ekonomikos bei pramoninės simbiozės principus. Medžiagos sudėtyje naudojami užpildai mažina pirminių žaliavų poreikį, didina regioninių išteklių panaudojimo efektyvumą ir prisideda prie transportavimo metu susidarančių emisijų mažinimo. Kadangi šie užpildai nereikalauja nei intensyvaus auginimo, nei papildomo apdorojimo, jų panaudojimas popieriaus kompozitų sudėtyje taip pat leidžia mažinti bendrą energijos ir cheminių medžiagų suvartojimą.

Rekomendacijos

1. Rekomenduojama rinktis uždaro ciklo popieriaus kompozitų formavimo technologiją, kuri dėl gamybos metu išlaikomų smulkiausių celiuliozės mikro- ir nanodalelių bei didesnės mielių koncentracijos, tikėtina, pagerintų medžiagos fizines-mechanines ir barjerines savybes.
2. Rekomenduojama nustatyti mielių koncentraciją lakštų formavimo mišinyje (medienos plaušienoje su užpildais) ir ištirti skirtingų mielių koncentracijų – 20 wt% ir 30 wt% sausosios masės – poveikį fizikinėms, mechaninėms ir barjerinėms savybėms.
3. Rekomenduojama pakartotinai atlikti aerobinio skaidumo bandymus 50–60 °C temperatūroje, kaip inokuliatą naudojant kompostą, kurio drėgmė yra 40–60 proc. Bandymams siūloma naudoti įrangą su automatiniu deguonies tiekimu.

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LIST OF PUBLICATIONS AND ATTENDANCE OF INTERNATIONAL CONFERENCES

List of publications:

1. **Markevičiūtė, Zita**; Varžinskas, Visvaldas. Plant-origin feedstock applications in fully green food packaging: the potential for tree-free paper and plant-origin bio-plastics in the Baltic Sea region // Sustainability. Basel : MDPI. ISSN 2071-1050. 2022, vol. 14, iss. 12, art. no. 7393, p. 1-15. DOI: 10.3390/su14127393. [Science Citation Index Expanded (Web of Science); Scopus; DOAJ] [IF: 3,900; AIF: 6,750; IF/AIF: 0,577; Q2 (2022, InCites JCR SCIE)] [M.kr.: T 004] [Input: 0,500]
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