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THE IMPACT OF SCIENTIFIC RESEARCH ON CORRUGATED BOARD ON THE LIFECYCLE OF PACKAGING

WPŁYW BADAŃ NAUKOWYCH NAD TEKTURĄ FALISTĄ NA CYKL ŻYCIA OPAKOWAŃ

ABSTRACT: Corrugated board, a highly versatile and sustainable material, is widely used in both transport packaging and shelf-ready packaging (SRP). This article examines how scientific research has significantly contributed to understanding and improving the lifecycle of corrugated cardboard packaging. Through advancements in material design, structural optimization, and enhanced recycling processes, research has extended the usability and durability of corrugated packaging, while minimizing its environmental footprint. By focusing on both transport and SRP packaging, this paper highlights how scientific innovation promotes a circular economy, reduces waste, and increases resource efficiency. Additionally, the studies emphasize the importance of raising public awareness and fostering engineering practices that contribute to the sustainable development of packaging systems, playing a crucial role in modern logistics and retail.
Key words: corrugated board, packaging lifecycle, transport packaging, shelf-ready packaging, sustainability, recycling

STRESZCZENIE: Tektura falista, niezwykle wszechstronny i zrównoważony materiał, znajduje szerokie zastosowanie zarówno w opakowaniach transportowych, jak i półkowych (SRP). Artykuł analizuje, w jaki sposób badania naukowe znacząco przyczyniły się do pogłębienia wiedzy i poprawy cyklu życia opakowań z tektury falistej. Dzięki postępom w projektowaniu materiałów, optymalizacji konstrukcji oraz ulepszonym procesom recyklingu, badania wydłużyły okres użytkowania i trwałość opakowań, jednocześnie minimalizując ich wpływ na środowisko. Skupienie się na opakowaniach transportowych i SRP podkreśla, jak innowacje naukowe promują gospodarkę o obiegu zamkniętym, redukują ilość odpadów oraz zwiększają efektywność wykorzystania zasobów. Dodatkowo, badania te wskazują na znaczenie zwiększania świadomości społecznej oraz wspierania praktyk inżynierskich, które przyczyniają się do zrównoważonego rozwoju systemów opakowaniowych, odgrywając kluczową rolę we współczesnej logistyce i handlu detalicznym.
Słowa kluczowe: ektura falista, cykl życia opakowań, opakowania transportowe, opakowania SRP, zrównoważony rozwój, recykling

1. INTRODUCTION

1.1 THE ROLE OF CORRUGATED BOARD IN THE MODERN PACKAGING INDUSTRY

Corrugated board is one of the most widely used materials in the global packaging industry, especially in the fields of product transport and presentation. Its unique properties, such as lightness, mechanical strength, and shock absorption capability, make it an ideal material for protecting goods during transport. Corrugated board can be easily tailored to various shapes and sizes, making it highly versatile for both large transport packaging and smaller shelf-ready packaging (SRP).

1.2 THE IMPORTANCE OF TRANSPORT AND SRP PACKAGING

Transport and shelf-ready packaging (SRP) play a crucial role in logistics and retail. Transport packaging must provide maximum protection for products during transport, storage, and distribution to minimize the risk of damage. In contrast, SRP packaging, aside from its protective function, serves a significant marketing role by allowing products to be displayed directly on store shelves in an attractive and easy-to-handle manner.

1.3 THE RISE IN DEMAND FOR SUSTAINABLE PACKAGING

In recent years, there has been a global increase in demand for sustainable packaging due to growing environmental awareness among consumers and regulatory pressures related to environmental protection. Corrugated board, as a fully renewable and easily recyclable material, has become one of the key solutions supporting a circular economy. Increased attention to sustainable development has led manufacturers and distributors to increasingly choose corrugated board, thereby minimizing the use of non-renewable materials and reducing the carbon footprint.

1.4 PURPOSE OF THE ARTICLE

This article aims to demonstrate how scientific research on corrugated board impacts the lifecycle of packaging, both for transport and shelf-ready applications. The article will discuss key issues related to packaging design optimization, environmental impact, and the role of corrugated board in promoting sustainable development. The analysis based on scientific research will show how advances in computational mechanics, material strength, and recycling technology contribute to extending the lifecycle of these packaging materials, reducing waste, and increasing recycling efficiency. Additionally, the article will emphasize the importance of raising public awareness about the role of corrugated board in the modern packaging industry.

2. LITERATURE REVIEW – SCIENCE IN THE DEVELOPMENT OF CORRUGATED BOARD PRODUCTS

2.1 MECHANICAL PROPERTIES OF CORRUGATED BOARD

Corrugated board, widely used in packaging, has a complex structure that impacts its strength and flexibility. Both theoretical and experimental research provides insights into essential mechanical properties, such as elasticity and compression strength. Notably, Aboura et al. [1] and Biancolini [7] examined the elastic behavior of corrugated board through experimental analysis, demonstrating that numerical modeling can predict this material's mechanical properties. The work of Buannic et al. [8] and Cheon and Kim [9] expands this analysis by using plate models that account for homogenization to simplify the structural analysis of corrugated board. Additionally, Bartolozzi et al. [4-5] developed an equivalent material model for sinusoidal cores in sandwich structures, enabling accurate mechanical property predictions when applied to corrugated board.

2.2 APPLICATION OF HOMOGENIZATION IN CORRUGATED BOARD ANALYSIS

Homogenization techniques are crucial for analyzing corrugated board, allowing for the transformation of a complex structure into a simpler equivalent material model. Doghri et al. [11] extended this technique to composite materials with diverse plastic properties, which is particularly beneficial for materials like corrugated board. Altmann et al. [2] further expanded homogenization methods to multiscale structures, useful for modeling advanced corrugated board properties. The research of Garbowski and collaborators often highlights the importance of homogenization in analyzing corrugated board [14,20], exploring aspects such as mechanical properties under different conditions. For instance, Garbowski and Borecki [15] investigated the impact of futuristic flute shapes on mechanical parameters and production costs, suggesting the potential to adapt the structure for more robust and economical materials.

2.3 IMPACT OF ENVIRONMENTAL FACTORS ON CORRUGATED BOARD PROPERTIES

Environmental factors, such as humidity and temperature, significantly affect corrugated board properties, which is crucial for transport packaging. Szewczyk and Głowacki [24] examined the impact of humidity on the strength indicators of corrugated board, while Beck and Fischerauer [6] used homogenization techniques to model board deformations during production, improving the understanding of external conditions on packaging stability. Cornaggia and colleagues [10] broadened this analysis with numerical modeling of humidity and temperature impacts on the mechanical properties of corrugated board, which is essential for the packaging industry.

2.4 STRENGTH ANALYSIS OF CORRUGATED BOARD PACKAGING

A critical aspect of the lifecycle of corrugated board packaging is strength analysis, which enables design optimization and resource efficiency. Mrówczyński and colleagues [21] focused on the influence of boundary conditions on the bending stiffness of multilayer corrugated board, essential for transport packaging. Andrzejak et al. [3] studied the effect of perforations on load-bearing capacity, directly affecting the safety and functionality of SRP packaging. In this context, Garbowski [13] described common mistakes in load-bearing capacity estimation, underscoring the importance of accurate analysis methods.

2.5 REVIEW OF CORRUGATED BOARD APPLICATIONS IN ENGINEERING AND PACKAGING

Lastly, it is worth noting the broad applications of corrugated board, not only as packaging material but also as a construction component. Garbowski and Rutkowski [18] reviewed applications in various fields, from engineering to packaging, highlighting the material's potential as a cost-effective and sustainable solution in engineering and logistics. Park et al. [22] analyzed the properties of corrugated board as a layered composite, further supporting its role as a versatile and environmentally friendly material.

2.6 ARTIFICIAL INTELLIGENCE AND SOFT COMPUTING IN CARDBOARD CHARACTERIZATION

In the realm of packaging innovations, artificial intelligence (AI) is increasingly being utilized to enhance material classification processes. A recent study by Rogalka et al. [23] compared two AI-based methods for classifying types of corrugated board using images of deformed cross-sections. The first method combined a genetic algorithm with a feedforward neural network, while the second employed a convolutional neural network (CNN) for direct image classification. Both approaches achieved high accuracy, with the CNN slightly outperforming the first method. This advancement underscores AI's potential to improve efficiency and precision in the packaging industry.

2.7 SUMMARY AND FUTURE OUTLOOK

The studies reviewed in this section indicate that research on corrugated board significantly impacts the optimization of its lifecycle, especially for transport and SRP packaging. By analyzing mechanical properties, using homogenization techniques, and examining environmental impacts, researchers contribute to extending the lifespan of corrugated board packaging and enhancing its eco-friendliness.

The visionary outlook on the future of corrugated board has been presented in the work of Garbowski and Borecki [15], who explored new flute shapes previously unused in production. Their analysis of these futuristic fluting profiles, differing from traditional sinusoidal shapes, reveals corrugated board's design potential and the possibility of adapting its structure for specific mechanical requirements. This innovative approach not only broadens the material's potential applications but also suggests the potential for reduced production costs and improved strength parameters. As a result, these studies offer new perspectives for the packaging industry, suggesting directions for the development of composite materials like corrugated board to further support sustainable development and resource efficiency.

3. CHARACTERISTICS OF CORRUGATED BOARD PACKAGING

3.1 MECHANICAL AND STRUCTURAL PROPERTIES OF CORRUGATED BOARD

Corrugated board is a composite material consisting of one or more layers of flat paper sheets (liners) and at least one layer of corrugated paper (fluting). Due to its structure, corrugated board combines lightness with exceptional mechanical strength. The corrugated layer acts as a cushion, absorbing shocks and impacts, which is crucial for protecting products during transport. Additionally, the appropriate selection of paper weight and the number of layers allows tailoring the properties of corrugated board to specific packaging requirements, such as resistance to compression, tension, moisture, and bending. The mechanical properties of corrugated board, such as elasticity modulus, edge crush test (ECT) strength, and box compression test (BCT) strength, are essential for evaluating its suitability for various packaging applications. Scientific research in this area enables a better understanding of the behavior of corrugated board under load, facilitating the optimization of packaging design.

3.2 TRANSPORT PACKAGING: FUNCTIONS AND REQUIREMENTS

Transport packaging made of corrugated board must meet several requirements to effectively protect products throughout the extended supply chain, which includes loading, transportation, storage, and unloading. Compression strength and structural stability are key characteristics determining the effectiveness of protection against mechanical damage. Besides the protective function, transport packaging must be easy to stack on pallets, which enhances logistical efficiency.

An important aspect emphasized by scientific research is the optimization of transport packaging in terms of material usage. Reducing packaging weight while maintaining its strength helps lower transportation costs and CO_2 emissions. Research on corrugated board layer compositions and their arrangement allows maximizing strength with minimal material use.

3.3 SHELF-READY PACKAGING (SRP): MARKETING AND LOGISTICS FUNCTIONS

Shelf-ready packaging (SRP) serves two essential functions: product protection during transport and direct product display on store shelves. SRP is designed to be quickly and easily opened, displaying its contents without the need for repackaging. This type of corrugated board packaging plays a vital role in retail, especially in large retail chains, where rapid product turnover and minimal time for sales preparation are crucial.

From a scientific and engineering perspective, SRP must meet requirements related to aesthetics, durability, and ease of use. In corrugated board research, particular emphasis is placed on ensuring SRP is not only functional but also easily recyclable after its lifecycle ends. Additionally, SRP design involves research on printing, color durability, and visual quality, which directly impacts brand perception by consumers.

3.4 TECHNICAL CHALLENGES IN DESIGNING CORRUGATED BOARD PACKAGING

Designing corrugated board packaging involves numerous technical challenges. The main objective is to create packaging that is lightweight, strong, and easy to recycle. One primary challenge is optimizing the mechanical properties of corrugated board to provide adequate product protection while minimizing material use. The proper design of packaging is crucial not only for product protection but also for production and transportation costs.

Research on new technologies in corrugated board production, such as boards with increased strength at reduced thickness, aims to decrease raw material consumption and reduce packaging weight. There is also significant interest in researching biodegradable coatings and barrier layers that could replace traditional, more difficult-to-recycle materials coating packaging.

4. THE IMPACT OF SCIENTIFIC RESEARCH ON PACKAGING DESIGN

4.1 RESEARCH ON THE OPTIMIZATION OF CORRUGATED BOARD PACKAGING DESIGN

The optimization of corrugated board packaging design is one of the key research areas aimed at increasing material efficiency and improving mechanical properties. Research focuses on analyzing the structure of the board itself, as well as methods of forming and designing packaging that must meet specific requirements related to product protection, transport efficiency, and aesthetics.

Modern research on packaging design optimization frequently utilizes advanced computer simulation tools that enable modeling the mechanical properties of packaging under various loads. Using tools like the finite element method (FEM), engineers can accurately predict packaging behavior under real-life operational conditions, allowing the creation of more efficient designs that minimize material use.

A key research issue is finding a balance between packaging strength and weight. Advanced research enables creating designs that provide adequate product protection while reducing raw material usage. Research on innovative solutions, such as corrugated board with varying thicknesses or internal structures, helps create packaging better suited to the demands of the logistics and retail industries.

4.2 APPLICATION OF COMPUTATIONAL MECHANICS IN PACKAGING STRENGTH ANALYSIS

Computational mechanics, particularly the finite element method (FEM), plays a crucial role in analyzing the strength of corrugated board packaging. These tools enable precise modeling of packaging mechanical behavior under various loads, such as vertical pressure, impacts during transport, or compression in warehouses.

Computer simulations allow for the prediction of packaging deformations in real conditions, helping engineers optimize their design. Research in this field shows that by using computational techniques, it is possible to significantly improve packaging strength without increasing its weight, which is essential for transport efficiency and environmental protection. The application of computational mechanics also enables the study of new, innovative solutions, such as variable layer thicknesses in different parts of the packaging, which allows for better adaptation to specific needs, for example, for products with irregular shapes or high weight. Additionally, simulations can be used to test packaging in different environmental conditions, such as high humidity or low temperatures, allowing for the creation of packaging more resistant to external factors.

4.3 INNOVATIONS IN PACKAGING DESIGN TO INCREASE DURABILITY AND REDUCE MATERIAL USAGE

In recent years, scientific research has led to numerous innovations in corrugated board packaging design, contributing to increased durability while reducing raw material usage. Key innovations include changes in the structure of the corrugated board itself, such as the use of multi-layer compositions or new types of fluting (e.g., microflutes) that offer better strength with less thickness.

Another innovative approach is the development of more environmentally friendly coatings and adhesives used in packaging production. Traditional coatings often complicate the recycling process because they contain materials that are difficult to separate from the paper. Current research focuses on developing biodegradable coatings that not only protect the packaging contents but also easily decompose in recycling processes, reducing their environmental impact.

Moreover, innovations in corrugated board packaging production include automation of production processes, which allows for greater precision in cutting and folding packaging. This enables the creation of more complex structures that better meet logistical and marketing requirements while minimizing production waste.

4.4 EXAMPLES OF INNOVATIVE PACKAGING DESIGNS

Many companies use scientific research findings to introduce innovative packaging solutions that enhance both durability and sustainability. One example is modular packaging that can be easily folded and adjusted to different product sizes. Other innovations include dual-function packaging, which can serve as transport packaging and then, with minimal modifications, become shelf-ready packaging (SRP).

Another example of innovation is “smart” packaging, which includes built-in sensors to monitor storage and transport conditions, such as humidity or temperature. These technologies allow for even greater product protection and waste minimization, which is crucial in industries such as pharmaceuticals and food.

5. LIFECYCLE OF CORRUGATED BOARD PACKAGING

5.1 LIFECYCLE ANALYSIS OF PACKAGING (FROM PRODUCTION TO RECYCLING)

The lifecycle of corrugated board packaging encompasses several key stages, starting from the production of raw materials, through packaging manufacturing, usage, and finally, the end-of-life stage, where it is either disposed of or recycled. Current research focuses on each of these stages to minimize the negative environmental impact of packaging while maximizing its functionality.

During the production phase, particular attention is given to the sustainable sourcing of raw materials, such as paper from renewable sources, including forests certified by the Forest Stewardship Council (FSC). Another significant challenge is optimizing the corrugated board manufacturing process to reduce energy and water consumption and lower $C0_2$ emissions. Scientific research on new production technologies aims to not only reduce the environmental footprint but also improve process efficiency, which has a direct impact on production costs and competitiveness.

The usage stage of packaging includes its utilization in logistics, storage, and retail. Corrugated transport packaging must provide maximum product protection, helping to minimize losses due to damage during transport. Shelf-ready packaging (SRP), in turn, must be functional and aesthetically pleasing to meet both logistical and marketing needs.
At the final stage of the lifecycle of corrugated board packaging, recycling plays a key role. Due to the high recyclability of corrugated board, most packaging can be reprocessed and reused in the production of new packaging, significantly reducing the demand for primary raw materials and lowering waste generation. Research on improving recycling processes, including the separation of board layers and reduction of material contamination, aims to further enhance this process.

5.2 RESEARCH ON EXTENDING THE USABILITY PERIOD OF CORRUGATED BOARD PACKAGING

One key research area is extending the usability period of corrugated board packaging to reduce its environmental impact by decreasing the need for producing new packaging. Longer-lasting packaging allows for multiple uses, reducing demand for raw materials and energy. Research on the durability of corrugated board in harsh conditions (e.g., high humidity, temperature fluctuations) and on material modifications that enhance its resistance to damage contributes to lengthening the lifecycle of packaging products.
Extending the usability period is particularly important for transport packaging, which must be durable enough to withstand multiple loading, transport, and unloading cycles without compromising its protective properties. In this context, research focuses on increasing compression resistance and improving the structural stability of packaging.

5.3 THE IMPORTANCE OF REUSE AND RECYCLING IN THE CONTEXT OF SUSTAINABLE DEVELOPMENT

Reuse and recycling of corrugated board are crucial elements of sustainable development. From the perspective of the packaging lifecycle, the possibility of multiple uses and easy recyclability make corrugated board one of the most eco-friendly packaging materials. Research on packaging reuse focuses on developing logistics systems that enable efficient recovery and reintegration of packaging into the supply chain. Corrugated board recycling is one of the most advanced recycling systems worldwide, with recovery rates often exceeding [85%]. The recycling process involves separating cellulose fibers, which can then be processed into new packaging products. Research in this area focuses on improving recycling efficiency, including reducing contaminants and increasing the number of cycles in which cellulose fibers can be reused.

5.4 THE IMPACT OF CORRUGATED BOARD PACKAGING ON WASTE REDUCTION AND CARBON FOOTPRINT REDUCTION

One of the most important aspects of the lifecycle of corrugated board packaging is its impact on the environment, including waste reduction and carbon footprint. Due to its recyclability and reusability, corrugated board packaging contributes significantly to reducing the amount of waste reaching landfills. Compared to packaging made from materials that are harder to recycle, such as plastic, corrugated board offers a much more eco-friendly solution.

Scientific research shows that appropriately designed corrugated board packaging can also help reduce the carbon footprint associated with packaging production and transport. Lightweight packaging requires less energy for transport, and its production from renewable resources (paper) generates lower $C0_2$ emissions than packaging made from plastic or metal materials.

6. IMPORTANCE OF CORRUGATED BOARD PACKAGING FOR THE CIRCULAR ECONOMY

6.1 THE ROLE OF SCIENTIFIC RESEARCH IN PROMOTING A CIRCULAR ECONOMY

The circular economy (CE) is an economic model aimed at minimizing waste and maximizing resource utilization through recycling, material reuse, and reducing the consumption of primary raw materials. Corrugated board, as a packaging material, aligns perfectly with the principles of the circular economy due to its high recyclability and renewability.

Scientific research plays a crucial role in optimizing the lifecycle of corrugated board packaging, enabling the effective implementation of circular economy principles in practice.
Scientists and engineers are developing new technologies for corrugated board production that minimize waste at every stage of the production process. This includes reducing energy and raw material consumption in manufacturing and optimizing packaging for reuse and recycling. Through this research, it is possible to close the lifecycle loop of packaging products, which significantly reduces environmental impact.
Additionally, research on new, biodegradable coatings for corrugated board packaging contributes to further sustainability, eliminating the need for non-ecological coatings and adhesives that would complicate the recycling process. These innovations enable corrugated board to better meet the requirements of a circular economy.

6.2 THE IMPACT OF SUSTAINABLE PACKAGING ON RECYCLING PROCESSES AND MATERIAL REUSE

One of the main aspects of the circular economy is the efficient processing of used materials for reuse. Corrugated board plays a key role here, as it is one of the most recyclable packaging materials. This capability allows for a reduced need for primary raw materials and limits the amount of waste reaching landfills. The corrugated board recycling process is already well developed, but scientific research is continually working to improve it. Modern recycling technologies allow for an increased number of cycles in which corrugated board can be reprocessed, directly impacting waste reduction. Besides traditional recycling processes, research is also focused on innovations such as using fibers derived from corrugated board for producing other materials, such as biodegradable composites or insulation.
Additionally, the reuse of corrugated board packaging before recycling is another vital element of the circular economy. Many companies are implementing return and reuse systems for packaging, which significantly extends their lifecycle. Research on packaging durability and on new technologies that enable multiple uses is essential for advancing this aspect of the circular economy.

6.3 EXAMPLES OF COMPANIES AND INDUSTRIES USING INNOVATIVE CORRUGATED BOARD PACKAGING SOLUTIONS

A growing number of companies across various industries are introducing innovative corrugated board packaging solutions that support the circular economy. In the e-commerce sector, for example, many companies are implementing reusable packaging that customers can return, reducing the need for new packaging. Examples include modular packaging that can be adjusted to different product sizes and shapes and reused in subsequent shipping cycles.
The food industry also uses innovative solutions, such as SRP packaging that can be transformed from transport packaging into display packaging without additional materials or processing. This type of packaging not only minimizes costs and handling time in retail locations but also reduces waste.
In the furniture and household appliances industries, corrugated board is increasingly used as a substitute for traditional packaging materials, such as styrofoam or plastic. Companies are introducing specially designed corrugated board packaging that provides the same level of protection with a significantly smaller environmental impact. Thanks to innovations in structure and strength, corrugated board is becoming more competitive with other materials.

6.4 CHALLENGES AND FUTURE OF SUSTAINABLE CORRUGATED BOARD PACKAGING

Despite the many successes in developing sustainable corrugated board packaging, there are still numerous challenges to overcome. One of the main challenges is ensuring that packaging is durable and resistant to mechanical damage while also being fully recyclable. The development of more advanced biodegradable coatings and adhesives is one of the most critical tasks researchers aim to solve.
Another challenge is educating consumers and companies about the benefits of recycling corrugated board packaging. Although the corrugated board recycling process is well-developed, it is not always fully utilized due to a lack of awareness about proper handling of packaging waste.
The future of corrugated board packaging lies in the ongoing development of production technologies that reduce raw

material and energy consumption while increasing functionality and the potential for multiple uses. Advancements in digitalization and automation of production processes may also bring significant benefits in terms of efficiency and waste reduction.

7. SOCIAL IMPACT OF RESEARCH ON CORRUGATED BOARD PACKAGING

7.1 INCREASING SOCIAL AWARENESS OF SUSTAINABLE PACKAGING

Scientific research on corrugated board packaging plays a crucial role in raising social awareness about sustainable development and eco-friendly packaging solutions. An increasing number of consumers and companies are beginning to understand the environmental impact of packaging materials. Through research based on lifecycle analyses (LCA) and technological innovations, consumers now have access to information that helps them make more environmentally conscious choices.

One of the primary educational outcomes of corrugated board research is the promotion of informed purchasing decisions. Consumers, equipped with knowledge about recyclability and the benefits of sustainable packaging, can make choices that support a circular economy. Consequently, demand is growing for products packaged in recyclable materials, placing pressure on manufacturers to adopt more eco-friendly solutions.

Additionally, educational campaigns led by industry organizations, supported by scientific research, encourage better management of packaging waste. The introduction of new recycling regulations and return programs, such as deposit systems, results from increased public and legislative awareness. In this way, research on corrugated board packaging directly influences consumer behavior and environmental policy.

7.2 EDUCATING CONSUMERS AND COMPANIES ON THE BENEFITS OF RECYCLING AND REUSING PACKAGING

Recycling and reusing corrugated board packaging are areas that require the involvement of not only producers but also consumers and the entire retail and industrial sectors. Scientific research contributes to developing effective recycling and reuse systems, and the results must be effectively communicated to both businesses and society.

In recent years, there has been a growing number of initiatives aimed at educating the public about recycling. Examples of such actions include informational campaigns in the media, ecological workshops, and educational programs in schools that promote responsible waste management. Thanks to these initiatives, awareness of the importance of waste segregation and the possibilities offered by corrugated board recycling is rising. Companies are increasingly engaging in Corporate Social Responsibility (CSR) activities, aimed at promoting sustainable practices, including using recyclable packaging and reusing resources.

Equally important is educating businesses, especially in the logistics and retail sectors, where corrugated board packaging plays a key role. Research on recycling and reuse opportunities provides companies with insights into optimizing packaging processes and waste management. For businesses, implementing sustainable development strategies is becoming increasingly important from a competitive standpoint, as customers are more attentive to the ecological approach of producers.

7.3 THE IMPACT OF SCIENTIFIC RESEARCH ON THE DEVELOPMENT OF ECO-FRIENDLY PRACTICES IN LOGISTICS AND RETAIL

Logistics and retail are sectors where innovations in corrugated board packaging can bring significant benefits to both the environment and operational efficiency. Research on transport and shelf-ready packaging (SRP) made from corrugated board contributes to the development of more sustainable practices in these industries.

In logistics, one of the key issues is reducing the weight and volume of packaging, which helps lower transportation costs and $C0_2$ emissions. Research on the optimization of corrugated transport packaging allows for the design of lighter and stronger packaging that protects goods with minimal raw material use. Innovations in this field, such as the use of variable thickness corrugated board or smart packaging that monitors transport conditions, help companies achieve their sustainable development goals.

In retail, SRP packaging plays a crucial role in enhancing the efficiency of warehousing processes and product display on shelves. Research on SRP packaging focuses on designing solutions that are both functional and aesthetically pleasing, which aids in product promotion and reduction of packaging waste. Sustainable SRP packaging can be easily recycled after use, reducing the amount of waste generated by retail operations. Additionally, research on packaging materials enables the creation of more environmentally friendly solutions that meet logistical and marketing requirements.

7.4 RESEARCH AS A TOOL FOR SUPPORTING THE DEVELOPMENT OF ECO-FRIENDLY PRACTICES

As more companies commit to achieving sustainable development goals, scientific research becomes crucial for developing and implementing innovative packaging solutions. This research provides companies with knowledge about modern technologies that can support more eco-friendly practices in both production and packaging use.

Scientists working with the private sector help companies identify opportunities to optimize packaging, warehousing, and transport processes, leading to more efficient resource utilization and waste reduction. Through the collaboration of science and industry, it is possible to develop innovative packaging materials that are not only efficient and durable but also easy to recycle or biodegrade.

For example, research on new forms of corrugated board and biodegradable coatings contributes to creating more eco-friendly alternatives to traditional packaging. Companies, by leveraging research results, can introduce more environmentally friendly products to the market, which not only helps protect the environment but also builds a positive brand image among consumers.

8. FUTURE OF CORRUGATED BOARD PACKAGING

8.1 PROSPECTS FOR THE DEVELOPMENT OF CORRUGATED BOARD PACKAGING: NEW TECHNOLOGIES AND MATERIALS

The future development of corrugated board packaging will be driven by growing demands for sustainable development, technological innovation, and regulatory changes related to waste management. Future corrugated board packaging will need to meet both logistical process optimization challenges and rising consumer expectations for eco-friendly products.

One of the key areas for future development will be further material optimization. Scientists are working on creating new forms of corrugated board with higher strength while using fewer raw materials. An example is the development of microflute board, characterized by reduced thickness but excellent mechanical properties, allowing for a decrease in packaging weight without compromising durability.

Additionally, new production technologies are being developed for manufacturing corrugated board from organic materials, such as plant waste or biopolymers. These innovations can significantly impact the sustainability of packaging, reducing dependency on primary resources and lowering greenhouse gas emissions associated with corrugated board production.

8.2 OPPORTUNITIES TO EXPAND THE USE OF SRP AND TRANSPORT PACKAGING IN VARIOUS INDUSTRY SECTORS

Corrugated board packaging already plays a key role in many industries, but its full potential has yet to be fully realized. In the future, a significant increase in the use of corrugated board packaging is anticipated in industries that have traditionally relied on other materials, such as plastic or metal.

In the e-commerce sector, with the rise of online shopping, demand for lightweight, durable, and eco-friendly packaging will grow. Corrugated board is an ideal solution due to its customizable structure for individual e-commerce needs and its easy recyclability by consumers. Innovations in packaging personalization, which allow for adjusting the packaging to diverse products, will also play an increasing role.

In the food sector, corrugated board can replace traditional materials such as styrofoam, especially for packing refrigerated and frozen goods. Research on moisture-resistant corrugated board suitable for low temperatures enables expanding its applications in food storage and transport. This makes it possible to create packaging that not only meets product protection requirements but is also more environmentally friendly.

8.3 THE ROLE OF COLLABORATION BETWEEN SCIENCE AND INDUSTRY IN THE FURTHER DEVELOPMENT AND IMPLEMENTATION OF INNOVATIONS

The future of corrugated board packaging largely depends on effective collaboration between the scientific sector and industry. Joint research and development projects involving both academic institutions and production companies enable faster implementation of innovative solutions that meet market requirements.

One of the most important aspects of this collaboration is the development of new packaging production technologies that reduce environmental impact while increasing operational efficiency. Scientists working with corrugated board manufacturers develop new manufacturing methods that reduce energy, water, and raw material consumption during production. These innovations may include developing more efficient, less energy-intensive recycling processes, as well as corrugated board processing techniques that improve its mechanical properties without increasing thickness.

Collaboration between science and industry is also key in establishing standards for sustainable packaging. Scientific research provides companies with data and tools to evaluate the environmental footprint of their products, which, in turn, influences strategic decision-making. Production companies can adjust their processes to meet growing regulatory requirements and consumer expectations.

8.4 FUTURE TRENDS IN SUSTAINABLE PACKAGING

In the coming years, the main trends in corrugated board packaging will involve further material optimization and sustainable practices. It is anticipated that new production technologies will emerge, enabling the manufacturing of packaging in an even more efficient way, with lower raw material and energy consumption. Digitalization and automation of production processes will also grow in importance, potentially contributing to increased precision in packaging production, waste minimization, and shorter production times.

Another key trend will be the development of smart packaging that can monitor storage and transport conditions, such as temperature, humidity, or vibration levels. These types of

solutions could be especially significant in industries such as pharmaceuticals or food logistics. Smart corrugated board packaging will combine functionality with a low environmental impact, making it an ideal solution for the future.

9. SUMMARY

9.1 KEY FINDINGS ON THE IMPACT OF RESEARCH ON CORRUGATED BOARD ON PACKAGING LIFECYCLE

Scientific research on corrugated board plays a crucial role in understanding and improving the lifecycle of packaging made from this material. Studies clearly show that corrugated board is an exceptionally versatile material, offering high mechanical strength while being environmentally friendly. The impact of this research includes the development of new production technologies, optimization of packaging design for strength and sustainability, and improvements in recycling processes, which significantly extend the lifecycle of packaging.

One of the key findings is that innovations in the design of corrugated board, such as reducing thickness while maintaining strength, allow for reducing the amount of raw materials used, which directly impacts the reduction of the carbon footprint of packaging. Research on biodegradable coatings and adhesives further enhances the sustainable nature of corrugated board, enabling full recycling of the material without quality loss.

9.2 IMPORTANCE OF RESEARCH IN THE CONTEXT OF SUSTAINABLE DEVELOPMENT

Research on corrugated board aligns with the global trend of seeking more sustainable solutions in the packaging industry. Thanks to scientific studies, corrugated board has become one of the leading materials supporting the circular economy, which aims to minimize waste and maximize resource use.

Studies on corrugated board packaging demonstrate how innovative design approaches can reduce waste and extend product lifecycles. Moreover, this research plays a key role in raising social awareness of recycling and reusing materials, which is essential for building sustainable practices among both consumers and companies. The packaging industry is constantly evolving, and scientific research contributes to the creation of new, eco-friendly products that support the responsible use of natural resources.

9.3 OPPORTUNITIES FOR FURTHER RESEARCH AND DEVELOPMENT DIRECTIONS FOR CORRUGATED BOARD PACKAGING

Although research on corrugated board has already yielded many valuable results, there are still numerous areas that can be further developed. One of the key development directions is the ongoing optimization of recycling processes to make them even more efficient and adaptable to changing market requirements. Studies on increasing the number of recycling cycles and improving the quality of recycled material can further reduce the need for primary raw materials.

Another area for future research is the development of smart packaging, which can monitor product transport and storage conditions. Combining sensor technology with eco-friendly materials like corrugated board could open up new possibilities in sectors requiring specific storage conditions, such as the pharmaceutical and food industries.

As sustainability demands increase, scientists will also need to explore ways to further reduce raw material use, both through improved packaging design and the development of new, biodegradable materials. Strengthening collaboration between research institutions and industry will be essential for further progress in this area, as this synergy enables faster implementation of innovations in the market.

9.4 THE ROLE OF SCIENCE AND INNOVATION IN THE FUTURE OF THE PACKAGING INDUSTRY

In the future, the role of science and research on corrugated board will become even more critical, especially in the context of rising consumer expectations and environmental protection regulations. Scientific innovations will not only drive the development of new materials and technologies but also influence how the packaging industry operates, from design and production to usage and recycling.

The packaging industry faces the challenge of reducing its environmental impact, and corrugated board, with its unique properties, is becoming a material of the future that can meet these demands. Science will play a vital role in ensuring that this material continues to be developed and optimized to meet future challenges, while contributing to building a more sustainable world.

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