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Ecological Aspects of the Production of Molded Paper Pulp Packaging: Generation and Treatment of Industrial Wastewater

ABSTRACT

The production of packaging from molded paper pulp represents one of the most promising solutions for improving the sustainability of the packaging and graphics industry thanks to the possibility of using recycled fibers, reducing the use of primary raw materials, and contributing to the principles of the circular economy. However, the process of production and recycling of paper pulp is characterized by intensive water consumption and the generation of significant amounts of industrial wastewater containing suspended matter, organic pollutants, lignin residues, chemicals from the processing process, and other contaminants. This review systematizes the available knowledge about the technological stages of production of molded paper pulp packaging, the sources of wastewater, and their potential impact on the environment. Special attention is paid to the role of recycling of paper materials, the application of circular economy principles in the graphic industry, as well as the importance of rational management of water resources during the production process. The basic characteristics of industrial wastewater from the pulp and paper sector are presented, along with an overview of mechanical, chemical, and biological methods of their treatment, with an emphasis on their possibilities, limitations, and contribution to reducing the burden on the environment. Also, modern trends in the development of more environmentally friendly technologies for the production and purification of wastewater are considered, including the reduction of water consumption, the closing of process water cycles, and the application of sustainable technological solutions. Analysis of the available literature indicates that the integration of efficient wastewater treatment systems with sustainable resource management is one of the key prerequisites for reducing the ecological footprint of the graphic and paper industry and the successful implementation of the principles of sustainable development.

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1. Introduction

The modern development of the graphic and packaging industry is aimed at finding materials and production processes that, in addition to meeting functional and economic requirements, enable reducing the negative impact on the environment. Special attention is paid to materials based on cellulose fibers, among which packaging made of molded paper pulp represents a significant alternative to conventional packaging materials. Its application is based on the possibility of using recycled paper fibers, a relatively simple shap-

ing process, the possibility of recycling and biodegradability, which opens up space for more efficient inclusion of paper waste in new production cycles (Su et al., 2018; Dey et al., 2020; Semple et al., 2022).

Paper and cardboard packaging occupies an important place in the modern packaging sector, thanks to a wide range of applications, convenience for printing, recyclability, and availability of raw materials. Materials based on cellulose fibers can be shaped into different geometries and adapted to the requirements of protection, transportation, and product presentation. At the same time, the use of recycled fibers allows extending the life cycle of paper materials and reducing the need to use primary raw materials (Kirwan, 2005; Hogarth, 2005; Riley, 2012). The historical development of molded fiber packaging shows that this technology is not new, but its importance is growing in recent years due to the increased need for more sustainable packaging solutions (Wever & Twede, 2007; Didone et al., 2017).

Molded paper pulp is a fibrous suspension that, after preparation and processing of the raw material, is shaped into a suitable product using a mold. Depending on the origin of the fibers, primary or secondary raw materials can be used, whereby recycled paper represents a significant raw material basis for the production of new paper and packaging products. The process of recycling paper includes a series of procedures that remove unwanted components, including residual graphic inks, adhesives, coatings, and other materials, after which the fibers are prepared for reuse (Biermann, 1996; Sixtra et al., 2006; Kirwan, 2011).

The characteristics of molded fibrous materials depend on the properties of the initial raw material, the length and morphology of the fibers, the way they are processed, the conditions of shaping and finishing. Recycled fibers may lose some of their original strength, swelling degree, and other functional characteristics during repeated processing cycles. However, modern processing procedures enable the improvement of material properties and their application in various areas of the packaging industry (Gurav et al., 2003; Vishtal & Retulainen, 2012; Debnath et al., 2022).

Molded paper pulp is of particular importance in the production of protective packaging, transport liners, trays, containers and other shaped packaging elements. The possibility of adjusting the geometry of the product to the requirements of the packaged product, as well as the possibility of combining mechanical protection with a relatively small packaging mass, represents significant advantages of this material. At the same time, the development of new molding technologies, including modern approaches to mold making, further expands the application possibilities of molded fibrous materials in industrial production (Martínez et al., 2016; Didone et al., 2017).

However, the environmental acceptability of molded fiber packaging cannot be viewed only on the basis of the properties of the final product. To assess the overall impact, it is necessary to consider the entire life cycle of the material- from the selection of raw materials and the preparation of fibers, through the production and design of packaging, to its use, recycling, and final disposal. In this context, the secondary flows created during production play a significant role, among which are solid residues and wastewater (Verghese et al., 2011; Silva & Pålsson, 2022).

2. Packaging made of molded paper pulp and recycled fibers

The process of manufacturing molded fiber products can be seen as part of a wider system of cellulose raw materials processing. In the case of primary fibers, the process includes raw material preparation, pulp production, cleaning, possibly bleaching, refining, and preparation for product formation. With recycled paper materials, the process is additionally focused on removing components that are not desirable in the new production cycle. This includes the removal of foreign materials, coating residues, adhesives, ink, and other impurities (Kirwan, 2005; Koch, 2006; Sixtra et al., 2006). Recycling of paper materials allows fibers to be re-introduced into the production system after use, thus reducing the need to use primary raw materials. However, this process simultaneously requires a certain amount of water and energy, and certain phases can lead to the creation of waste streams with an increased content of suspended and dissolved substances. Therefore, the sustainability of recycling should not only be viewed through the amount of reused material, but also through the efficiency of using water, energy, and auxiliary chemicals (Su et al., 2018; Haile et al., 2021).

The composition of the raw material is of particular importance for the quality of the obtained pulp. Different types of paper waste can contain different amounts of ink, coatings, adhesives, and other additives, which is why the proper separation of waste paper is one of the important prerequisites for obtaining high-quality recycled fibers. In addition, the choice of fiber source affects their physical and mechanical characteristics, and therefore the properties of the final packaging (Dey et al., 2020; Semple et al., 2022). The use of recycled cellulose fibers in packaging is related to the concept of replacing materials based on fossil resources with materials from renewable or secondary sources. Cellulosic materials can represent a potential alternative to certain plastic packaging solutions, especially in cases where the required properties of the product can be achieved without the application of complex barrier systems. However, applications requiring increased resistance to moisture,

oil, grease, or gases may require additional coatings or functional layers, thus changing the overall material composition and complexity of the recycling process (Su et al., 2018; Schenker et al., 2021; Semple et al., 2022).

Therefore, modern research is increasingly directed towards the development of cellulosic materials with improved barrier properties, as well as towards the use of alternative fibrous raw materials. In addition to wood fibers, various non-wood plant raw materials and agro-industrial residues are examined, which further expands the potential of circular biomass use in paper and packaging production (Kamoga et al., 2013; Karlovits et al., 2020).

3. Waste generation in the graphic and packaging industry

The graphic industry includes a large number of interconnected processes, from the production of paper and cardboard to printing, finishing, and production of finished graphic and packaging products. During these processes, different types of waste are created, which, according to their origin and characteristics, can be classified into material remains, technological and chemical waste, as well as emissions into the air (Figure 1). Material residues include waste paper and cardboard, scraps and defective products, while technological-chemical waste includes residues of inks, solvents, cleaning agents and various filtrates (Magrini et al., 2020; El Salam, 2023). A special problem is the flows that occur in paper recycling processes. Their composition depends on the origin of waste paper, previous graphic processes, and applied chemical agents. Inks, coatings, and adhesives can reach the water phase during defibering and cleaning, which is why wastewater with a complex composition is formed. In addition to suspended fibers, such waters may contain organic matter and other components originating from the raw material and the technological process (Wen et al., 2016; Hubbe et al., 2016).

Waste management in the graphic industry therefore requires an integrated approach that encompasses all material flows. Prevention of waste generation, rational use of raw materials and water, reuse of materials, and efficient purification of waste streams are interrelated activities. Their goal is not only to reduce the amount of waste, but also to preserve the material and energy value of the resources found in the production system (Tencati et al., 2016; Megale Coelho et al., 2020).

In this sense, the problem of wastewater cannot be separated from the overall industrial waste management system. Water used during production can become a carrier of fibers, ink, adhesives, and other components, so its uncontrolled discharge can represent an additional burden on aquatic ecosystems. The impact of pulp and paper industry wastewater on aquatic ecosystems has been the subject of many years of research, with particular consideration being given to organic load, suspended matter, and the presence of various difficult-to-degrade compounds (Poole et al., 1978; Lindholm-Lehto et al., 2015; Singh et al., 2022).

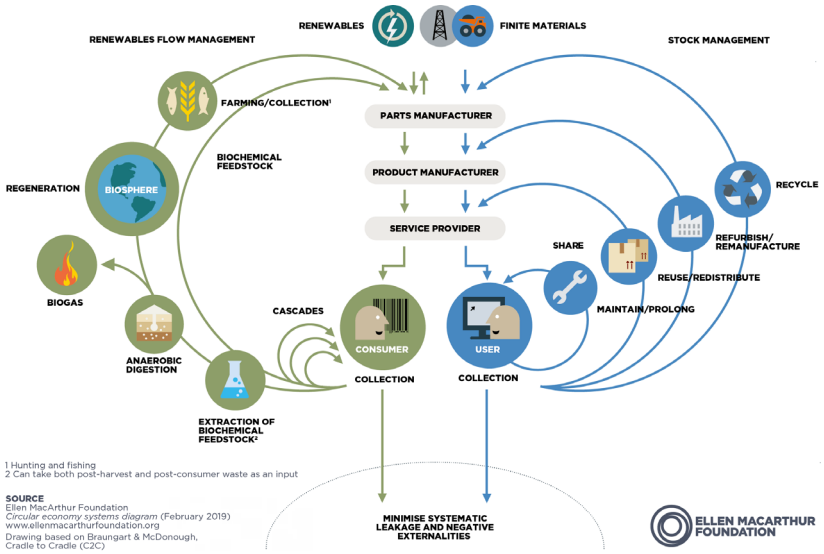
3.1. Circular economy as a framework for materials and waste management

The traditional linear production model is based on the principle of taking natural resources, processing them into products, using them, and finally discarding them. Such a system implies a continuous flow of primary raw materials and the generation of waste after the end of the product's life cycle. In contrast, the circular economy (Figure 2) seeks to keep materials and products in use as long as possible and to reduce the loss of their material value (Geissdoerfer et al., 2017; Korhonen et al., 2018). The concept of circular economy was developed through different approaches to resource management, and in modern literature it is associated with the principles of reducing resource consumption, reuse, recycling, and re-inclusion of materials in production flows (Winans et al., 2017; Popović & Radivojević, 2022). Unlike the linear model, in the circular system waste is not viewed exclusively as the end product of the process, but as a potential secondary raw material whose value can be preserved by appropriate technological procedures.



(a) (b) (c) (d)

» **Figure 1:** *Overview of the different types of waste generated by the graphic industry: a) Material remains (Lundberg Tech, 2026), b) Chemical waste (GMG EnviroSafe, 2026), c) Gas emissions (Future US, 2021), d) Wastewater (EDG Ltd., 2026)*



» **Figure 2:** *Circular economy systems diagram (Ellen MacArthur Foundation, 2019)*

In the graphic industry, the principles of the circular economy can be applied to different levels of the production system. At the level of raw materials, this means increasing the use of recycled fibers and other secondary materials. At the production level, it includes the rationalization of water and energy consumption, the reduction of waste generation, and the optimization of technological processes. At the product level, it involves designing packaging that can be reused, recycled, or otherwise returned to the material cycle (Kirchherr et al., 2017; Silva & Pålsson, 2022). The closure of water courses is of particular importance. In the production of paper and molded fibrous materials, water is an important process resource, which is why the reduction of its consumption and the possibility of reuse after appropriate treatment can contribute to greater system efficiency. Thus, the relationship between packaging production and wastewater treatment is viewed as part of a wider resource management system, rather than as two separate processes. However, the circular economy involves more than just increasing the recycling rate. According to Korhonen et al. (2018), the concept has certain limitations related to the physical limits of material cycles, energy requirements, and the possibility of material quality loss during repeated cycles. Therefore, it is necessary to simultaneously consider the technological, economic, and environmental justification of the proposed solutions (Neves & Marques, 2022).

For the paper and packaging industry, this approach is particularly important, as it enables the connection of paper recycling, fiber reuse, rational water management, and treatment of the generated waste streams into a single system. In this way, the production of molded fiber packaging can be seen as part of a wider strategy of closing material flows.

4. Industrial wastewater

Wastewater is water whose physical, chemical, or biological parameters have changed due to its use in a specific production or other process. Industrial wastewater can have a very complex composition, which depends on the type of industry, the raw materials used, the technological process, and the chemical agents used. Their treatment represents an important segment of environmental protection, especially when the water after use is discharged into a natural recipient or public sewage system (Povrenović & Knežević, 2013).

The characterization of wastewater is the basis for choosing the appropriate treatment procedure. Physical characteristics include, among other things, the content of suspended and dissolved substances, while chemical characteristics refer to the presence of various organic and inorganic components. Chemical oxygen demand (COD) and biochemical oxygen demand (BOD) are especially used to assess the organic load, while the pH value is one of the basic parameters that affects the course and efficiency of numerous treatment processes (Povrenović & Knežević, 2013).

Wastewater from the pulp and paper industry can contain different groups of pollutants. Their composition depends on the production process and the raw materials used, but may include suspended matter, dissolved organic matter, ink, lignin components, and various hard-to-degrade compounds. The complexity of the composition determines the need to combine different purification procedures (Badar & Farooqi, 2012; Hubbe et al., 2016). Therefore, the choice of treatment must be adapted to the characteristics of the specific waste stream. Depending on the degree of pollution, mechanical, physical-chemical, chemical, biological, and advanced oxidation processes can be applied. Com-

bining several procedures enables the achievement of an appropriate degree of purification and can contribute to a more efficient use of water in the production process (Hermosilla et al., 2015; Hubbe et al., 2016).

4.1. Wastewater treatment procedures from the graphic industry

The treatment of industrial wastewater is most often organized as a multi-stage system in which different groups of pollutants are removed by appropriate processes. Mechanical treatments represent one of the initial stages and aim to remove large particles, fibers, and suspended matter. These processes include sieving, filtration, sedimentation, and flotation. Their application can reduce the load on the subsequent stages of treatment and enable more efficient removal of smaller particles and dissolved components (Badar & Farooqi, 2012; Hubbe et al., 2016).

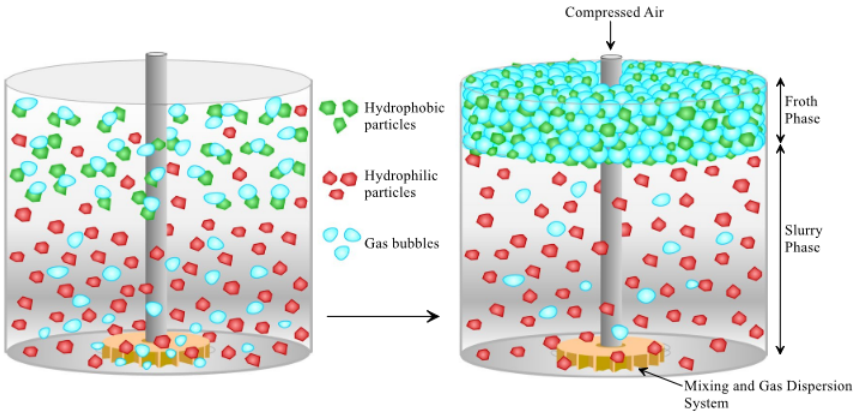
Flotation (Figure 3) is based on the separation of particles that, due to differences in density and interaction with gas bubbles, can be separated on the surface of the water. In systems where light fibrous particles, pigments, or certain organic components are present, flotation can be an effective way to separate them. The application of this procedure is particularly important when it is necessary to reduce the concentration of suspended substances before the next stages of processing.

Coagulation and flocculation belong to physico-chemical procedures that have a significant application in the treatment of industrial wastewater. Coagulation involves the destabilization of colloidal and suspended particles by the addition of a suitable coagulant, while flocculation enables their mutual connection and the formation of larger aggregates, flocs. The resulting flocs can then be separated by settling or flotation (Hubbe et al., 2016; Vasiljević et al., 2023).

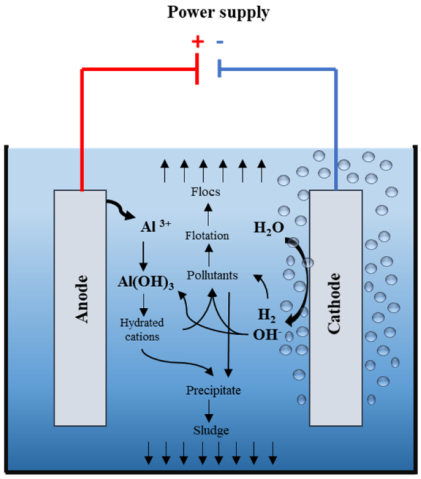
Coagulation processes can be realized using various compounds based on aluminum or iron. The effectiveness of coagulation depends on a number of factors, among which are the characteristics of wastewater, pH value, concentration of pollutants, type and dose of coagulant, as well as time and intensity of mixing. Therefore, the optimal process conditions are most often determined experimentally, using standardized laboratory procedures such as the JAR test (Vasiljević et al., 2023). Polyaluminum chloride is one of the groups of coagulation agents used to remove suspended and colloidal substances from different types of wastewater. Its action is related to the neutralization of particle charges and the formation of hydroxide species that enable the removal of pollutants from the aqueous phase. The influence of pH and coagulant concentration on the efficiency of this process has been confirmed by research on various industrial wastewaters (Zhang et al., 2023). Coagulation can be combined with flocculation and flotation, which enables a more efficient separation of the formed aggregates. Adding a polymeric flocculant can contribute to the creation of larger and more stable flocs, which are more easily separated from the aqueous phase. This combined approach is particularly important in waters with a high content of suspended and organic matter (Vasiljević et al., 2023).

In addition to classical chemical coagulation, electrochemical procedures are also being investigated. Electrocoagulation (Figure 4) enables the creation of coagulation species on site, using electrodes based on aluminum or iron. This procedure is being investigated as a possibility for the treatment of wastewater from the pulp and paper industry, especially due to the potential for the simultaneous removal of suspended and organic matter (Katal & Pahlavanzadeh, 2011; Bassyouni et al., 2023).

Biological treatments represent another important group of processes, especially when wastewater contains biodegradable organic matter. Their effectiveness depends on the biodegradability of the compounds present and the conditions in which the microorganisms perform their function. In the case of pulp and paper industry wastewater, biological processes can be part of combined systems in which previous physicochemical processes reduce the water load (Hubbe et al., 2016; Toritsegbone et al., 2024).



» **Figure 3:** *Schematic diagram of flotation (Pawlik, 2022)*



» **Figure 4:** *Schematic diagram of electrocoagulation (Almukdad et al., 2021)*

Advanced oxidation processes represent an additional possibility for the removal of hard-to-degrade organic compounds. Their application is based on the generation of highly reactive oxidation species that can decompose complex organic molecules. In the pulp and paper industry, the application of various advanced oxidation technologies has been investigated, especially for streams containing resistant organic components (Hermosilla et al., 2015).

The modern approach to the treatment of industrial wastewater increasingly involves combining different methods. Mechanical processes may precede chemical ones, while chemical or physicochemical treatments may be followed by biological treatment or advanced oxidation processes. The choice of combination depends on the initial composition of the water, the required quality after treatment, the possibility of reusing the water, and the requirements for its final disposal (Badar & Farooqi, 2012; Hubbe et al., 2016).

4.2. Wastewater produced in the production of molded fiber packaging

In the context of the production of packaging from recycled paper pulp, the problem of wastewater is particularly related to the fact that the pulping and preparation process takes place in the presence of a significant amount of water. During the process, paper fibers, ink, adhesives, coatings, and other components present in the secondary raw material can pass into the water phase. In this way, the water used in the production process becomes a technological waste stream whose composition depends on the type of input paper and process conditions. Such water represents a characteristic example of the connection of material and water flow in a circular system. On the one hand, paper recycling enables the reuse of cellulose fibers and the extension of their life cycle. On the other hand, the recycling process itself generates wastewater that needs to be treated in order to prevent the transfer of pollutants into the environment. A sustainable system therefore requires simultaneous management of both solid and liquid waste streams.

This is precisely why the treatment of wastewater generated in the production of molded fibrous materials is an important segment of the overall sustainability of this packaging solution. Effective treatment enables the reduction of the concentration of suspended and organic substances, while the possibility of reusing the treated water additionally contributes to the rationalization of the consumption of water resources. At the same time, the resulting sediment and separated fibrous matter can represent a potential secondary material, provided that their composition and quality allow for safe reuse. A review of the available literature shows that the treatment of pulp and paper industry wastewater is increasingly being considered within an integrated resource management system. In addition to the removal of pollutants, the possibility of water regeneration, the use of separated materials, and the reduction of the total consumption of resources are of increasing importance (Hubbe et al., 2016; Haile et al., 2021). Such an approach is in accordance with the basic principles of the circular economy, according to which the goal is to reduce the loss of materials and energy and retain resources in the production system as long as possible.

5. Conclusions

Molded paper pulp packaging represents a material solution that enables the use of recycled cellulose fibers and their re-inclusion in the production cycle. Its characteristics, wide application potential, and recyclability contribute to its importance in the modern development of sustainable packaging. However, the sustainability of this solution cannot be assessed only on the basis of the origin and properties of the final product, but requires consideration of the complete production system, including the consumption of water, energy, auxiliaries and the generation of waste streams.

The production of pulp from recycled paper is associated with the generation of wastewater that may contain fibers, suspended matter, organic components, remnants of ink, adhesives and other pollutants. Therefore, the treatment of these waters represents an important element of managing the impact of the graphic and packaging industry on the environment. Mechanical, physico-chemical, chemical, biological and advanced oxidation processes represent different possibilities, the application of which can be combined depending on the characteristics of the specific waste stream. Coagulation and flocculation are of particular importance, because they enable the destabilization and separation of suspended and colloidal substances,

while combining with flotation can further improve the separation of formed aggregates. The selection of the appropriate coagulant, its dosage, and process conditions is an important part of treatment optimization. At the same time, the possibility of reusing treated water and using separated material opens up additional possibilities for closing material and water flows.

Based on the reviewed literature, it can be concluded that sustainable wastewater management in the production of molded fiber packaging cannot be viewed in isolation from the broader concept of circular economy. Connecting the recycling of paper materials, rational water consumption, appropriate wastewater treatment, and reuse of separated materials is the basis for the development of a more efficient and sustainable production system. In this context, research and optimization of physico-chemical wastewater treatment procedures are important not only from the aspect of achieving the required water quality, but also from the aspect of improving the overall material and ecological efficiency of production.

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