

Manufacturing of Form-molded Pulp Products (FMPPs) in the Papermaking Industry – A Review

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The article reviews the history of the production of form-molded pulp products (FMPPs) and the current value of their production. The discussion includes fibrous intermediates and additional materials used to produce these products, the categories and properties of FMPPs, and principles of operation of machines used to produce them. It compares vacuum and overpressure molding techniques, and current and future trends in FMPPs production. FMPPs are produced from fibrous secondary and primary papermaking pulps, as well as other waste intermediates, the use of which can contribute to reducing the costs of producing these products. It was found that over the past dozen or so years, the state of knowledge on improving the strength properties of FMPPs and the use of biodegradable aids to improve their properties, including barrier properties, has significantly expanded. Drawing not yet published in review articles, showing devices for producing FMPPs using hydraulic molding and pressurized air molding methods are presented in a descriptive and comparative form used in the industry at the turn of the 1950s and 1960s. Possible future directions are considered for FMPPs developments in technology and further commercialization.

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INTRODUCTION

The prices of industrial products and packaging are primarily affected by the cost of raw materials, the cost of performance of unit production operations, and the scale of production. In the production of industrial products and packaging, the two former criteria are usually met by the use of synthetic, thermoplastic polymers. Such materials are relatively inexpensive, and they can be formed into various shapes by heating, injecting, or pressing. For this reason, various synthetic polymers have become a popular material for the production of many products and packaging in the second half of the previous century and they still are (Andrady 2011; Greyer *et al.* 2017; Horejs 2020; MacLoed 2021). A prime example is expanded polystyrene (EPS). The main disadvantage of synthetic polymers, however, is their low susceptibility to biodegradation (Song *et al.* 2009; Briard *et al.* 2018). Even in the case of the plastic products that are susceptible to degradation by UV and oxygen, it does not proceed completely (Hann *et al.* 2017; Das *et al.* 2021). That is why used plastic products are the main type of pollution of land areas and water receivers in the world (*e.g.*, garbage dumps, junk islands in the oceans), as well as air in the event of their combustion (Barnes *et al.* 2009; Jembeck *et al.* 2015; Geyer *et al.* 2017; Horejs 2020).

Because of the threat that large quantities of products made of synthetic polymers pose to the environment, regulations have been introduced in many countries implementing restrictions, bans, severe fines, and heavy taxes on producers of plastic packaging (Government of Canada 2020; Zhou *et al.* 2020). For example, China and Taiwan banned the use of Styrofoam containers in 1999 (Didone *et al.* 2017). The European Union introduced the SUP (single-use plastic) directive – a legal act concerning the restriction of the use of such plastic products (Taxology 2025) [*e.g.*, those made from polystyrene foam (EPS)]. The media has played a significant positive role in raising awareness of the harmful impact of SUP on the natural environment in many countries of the world. These factors have caused consumers to become more willing to buy products in which the SUP was replaced by products made of natural origin materials that can be recycled and composted. One class of such alternative, bio-based products employs papermaking fibrous pulps, and it processes them using the form-molding (FM) technique (Garcia and Robertson 2017; Zhang *et al.* 2022).

In recent years, this topic has begun to arouse great interest. However, the number of scientific articles on this issue can still be considered small. This is certainly due to the lack of devices for manufacturing production molds for FMPPs and laboratory devices for such production in paper laboratories. In recent years, several review articles on the subject of FMPPs have appeared in the literature, such as Didone *et al.* (2017); Su *et al.* (2018); Zhang *et al.* (2021); Sengupta *et al.* (2020); Dey *et al.* (2020); Debnath *et al.* (2022); and Semple *et al.* (2022). These articles have presented the general concept of manufacturing these products or this concept and, more broadly, selected aspect(s) of FMPPs technology.

This paper is of the latter type. In addition to the general aspects of this technology (history, examples), which have been dealt with by other authors (although presented in a different way), it presents in more detail the issue of the categories of FMPPs (expands their number) and type of equipment used for the production of FMPPs, including those used to produce such products by strongly wet-pressed, hydraulic, pressurized air, and injection FM techniques. These devices and the principles of their operation are described in greater detail than in recently published articles of similar character. The paper also refers to the current state of production of FMPPs previously produced by hydraulic molding and pressurized air molding methods, the production of which is beginning to

revive (production of bottles using latter of method). In addition, the method of producing FMPPs with high barrier and strength properties (e.g. buckets and bowls) and the chemicals used in the past to obtain such effects. In this context, currently proposed methods for improving such properties of FMPPs are also reviewed. The paper ends with a presentation of current and future trends in the development of FMPPs production.

THE HISTORY OF PRODUCTION OF FMPP, THEIR EXAMPLES, AND THE CURRENT VOLUME OF PRODUCTION

The technique of manufacturing various molded pulp products, which are mostly three-dimensional in form, has a long history. The process, which involves depositing water-dispersed fibers on a sieve having the shape of the product and then drying them, became known to the world in 1890, when M. L. Keyes was granted a patent for protection of this technique (Keyes 1890; Tweede and Wever 2007; Didone *et al.* 2017) and soon after managed to develop a device for producing FMPPs (Keyes 1903). A characteristic feature of FM is the ability to form a whole three-dimensional product without the need first to produce cardboard and its processing by cutting or rolling and finally gluing (Casey 1961).

The first industrial machine was designed for producing egg trays by Joseph Coyle and developed after the First World War. In 1920, the use of this technique for producing packaging for other products requiring protection (light bulbs, fruits, *etc.*) was patented, thanks to which, in the years 1920-1940, the implementation of molded pulp products slowly increased (Didone 2020). In the 1950s and 1960s, a lot of FMPPs were produced using the FM technique, even television and radio cabinets, furniture components, molded luggage (Fig. 1A), different panels, glove compartments, gear covers, and bucket seats (Emery and Emery 1966; Głuchowski 1969) (Fig. 1B).

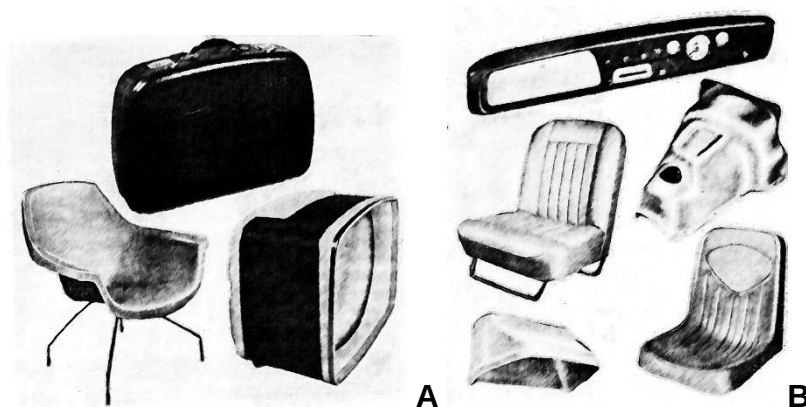


Fig. 1. Different FMPPS produced in the past using FM method

At the beginning of the 1970s, however, the development of production of such products was slowed due to the widespread use of plastic foam packaging and thermoplastic polymers for making parts of industrial products. It was only at the beginning of the 1990s that FMPP production started to grow again due to the growing interest of customers in the impact of the products they buy on the natural environment (Su *et al.* 2018; Didone 2020).

One of the most important FMPPSs today is still egg trays. They were manufactured in two main types: 36-eggs nest and those with a lid and a snap closure with sockets for up to 6, 10, 12, or 18 individual eggs (Emery and Emery 1966; Anon. 1967; Leman 1968; Drzewińska 2010).



Fig. 2. Examples of FMPP products. Egg tray (A), raspberry container (B), flowerpot (C), catering container (D), cup (E), alcohol bottle packaging (F), bottle with cork (G), protective corner (H), molding for industrial product packaging (I), containers for hospitals and healthcare (J), and the assembled part obtained by injection molding (K) (all photographs modified by the author into a drawing)

Examples of other popular FMPPs today are as follows (Fig. 2) (Haber 1989; Tomczuk 1989; Didone *et al.* 2017; Palenik 1954):

- Those used to hold or protect other products (*e.g.*, fruit trays, vegetable trays, flower pots, bottle covers for expensive alcohol, bread trays, bottles, jars).
- Those used to hold and protect food service products, *i.e.*, ready-to-eat meals (food trays, cups, plates, clamshells).

- Fittings for securing industrial products inside cardboard packaging (protective and shock-absorbing fittings) for expensive cosmetics, electronic devices, sensitive-to-impacts glassware (*e.g.*, bulbs, bottles with chemicals), as well as corners for securing edges of different products).
- Disposable containers used in healthcare facilities and medical devices.
- Household goods (bowls, buckets, bathtubs, flower pots, globes).
- Parts of industrial products such as loudspeaker cones, furniture components, elements of car upholstery (storage compartments), gear covers, TV and radio cabinets, and molded luggage.

Currently, FMPP production is in a phase of dynamic development, both in terms of technology and technical aspects. The world is transitioning towards eco-friendly and sustainable packaging solutions, which increases the demand for biodegradable packaging and storage solutions. For example, it is expected that various end-use industries, such as food & beverage, healthcare, and electronics, will use molded pulp packaging solutions in the future.

According to statistical data calculated using the CAGR model, in 2024 the value of papermaking products manufactured using the FM method in the world grew from 8,537 million dollars in 2020 to 10,219 million dollars in 2024 (FMI 2025). The pulp molding machine market also reports positive data. The market is expected to register a CAGR of 3.7% and reach a valuation of USD 1.1 billion from 2023 to 2033 (FMI 2025).

MATERIALS

Fibrous Intermediates Used to Make FMPPs

Fibrous intermediates used in papermaking can be divided into those obtained from wood, waste paper, and non-wood raw materials. Among these, one can distinguish those of relatively low quality and low price [(*e.g.*, undeinked, only mechanically cleaned waste paper pulp, old corrugated containers (OCC) pulp, own broke (secondary stock) pulp, knotter/screening pulp, reclaimed/recovered pulp], medium quality and medium price (*e.g.*, deinked waste paper pulp, unbleached high-yield kraft/sulfite pulps, groundwood, thermomechanical pulp - TMP), as well as high-quality ones of relatively high price such as bleached kraft/sulfite ECF, TCF pulps, BCTMP). All these intermediates require dispersal as individual fibers in a suspension of the appropriate concentration. Often the material is delivered to the FMPP plant in dry form (bales of compressed pulp sheets). In such cases, a certain deterioration of their properties can be expected as a result of their drying. Some of the FMPPs plants can be located in pulp and paper plants. In this case, they can obtain the fiber semi-finished product on their own from wood or waste paper. This allows the production of FMPPs from undried fiber pulp, with better strength properties (Dey *et al.* 2020).

It is obvious that in the case of FMPPs, which in many cases are intended to protect cheap products (egg trays, fruit/vegetable trays) or non-fragile heavy products (machine parts), their price should be low, and in such cases it will be preferable to use the cheapest possible fibrous intermediates for their production. In this cases, one can therefore consider using pulps from the first of the above-mentioned groups or mixtures of fibers from this group and from the second group. Some of these pulps, such as waste paper, knotter/screening, and reclaimed/recovered pulps, can be characterized by low strength

properties and lower dimensional accuracy (Dey *et al.* 2021). In the case of using FMPPs for packaging, for example, machine parts, this is not so important because the walls of these FMPPs are characterized by considerable thickness, and the FMPPs themselves have a multicellular structure given to them in order to maximize their cushioning properties (Zhang *et al.* 2022). When selecting a fibrous intermediate for the production of FMPPs, it should also be taken into account that cumulative energy to produce recycled pulp can be, *e.g.*, 27% lower, than for production of virgin pulp (Dey *et al.* 2021).

The importance of the properties of the fibrous intermediates used to manufacture FMPPs increases with the reduction of their wall thickness, the need to obtain well-shaped edges of the product, and the change in the type of FMPPs. FMPPs belonging to the *transfer-pressed* category, and especially *thermoformed* and *injection-molded*, require the use of better-quality fibrous semi-finished products. The requirement to use this type of fibrous semi-finished product to manufacture these categories of FMPPs also results from their use, *e.g.*, for the production of tableware, or as packaging whose application requires high standards in terms of the appearance and its physical, chemical, and microbiological purity (packaging for processed food, expensive cosmetics, pharmaceuticals, or expensive electronics).

For premium items it may be necessary to use cleaner, better quality, and more expensive fibrous intermediates such as deinked and chemically treated (*e.g.*, with H₂O₂, cleaned using a dispergation stage) waste paper pulps, BCTMP pulp, or bleached pulps, including even TCF kraft or sulfite pulps, because fibrous intermediates such as only mechanically cleaned waste paper pulps, groundwood and TMP, ECF kraft and sulfite pulps may contain particles of printing ink, stickies, bacteria or fungi, resin substances, and chlorine compounds, respectively (Su *et al.* 2018; Sengupta *et al.* 2020; Zhang 2022).

Recently, the types of fiber semi-finished products used in FMPPs research were analyzed quite thoroughly, *e.g.*, by Debnath *et al.* (2022) and Liu *et al.* (2023). The fiber types considered has included kraft pulps (Aguerre and Garvazzo 2016; Dislaire *et al.* 2021a), high-yield wood and bamboo pulps (Wang *et al.* 2021), chemi-mechanical pulps (Kirwan 213; Zhao *et al.* 2020; Dislaire *et al.* 2021a), ONP pulps (Corwin 1972; Ahn 1994; Gavazzo *et al.* 2003, 2005; Dislaire *et al.* 2021a), recycled cardboard pulps (Dislaire *et al.* 2021a), and old corrugated container pulps (Kirwan 2013; Aguerre and Gavazzo 2016).

In addition to purity and price, paper product manufacturers have recently also been taking into account the origin of fibers. This origin has an impact on the perception of FMPP products in terms of ecology. In the case of these fibers coming from waste paper, waste fibrous raw materials from agriculture (straw, bagasse, banana stems), stalks of wildy fast-growing plants [(*e.g.* bamboo, maturity cycle only few years), oil palms] or invasive plants they seem to the customer to be much more eco-friendly (Chen *et al.* 2012; Vargas *et al.* 2012; Curling *et al.* 2017; Liu *et al.* 2020; Rattanawongkun *et al.* 2020; Prasertpong *et al.* 2021; Liu *et al.* 2023), than in the case of their origin from natural forests, whose exploitation for economic purposes in many regions of the world has recently been severely restricted.

Fibrous agricultural waste also has attracted interest by the FMPPs industry. Pulps from other non-wood raw materials, such as hemp, flax, bamboo, and grass, can also be used in this capacity (Chen *et al.* 2012, Liu *et al.* 2020; Su *et al.* 2018; Zhang *et al.* 2022; Debnath *et al.* 2022).

The criteria that FMPP producers should also take into account are their properties, such as:

- Fines fraction. The fines content will affect the dewatering rate, moisture absorption and dimensional stability of these products (Sung *et al.* 2004; Debnath *et al.* 2022).
- Kind of fibers and fiber properties: The stiffness of the fibers, in their wet condition, will affect the density of the resulting molded pulp or paper products, their thickness, strength, and porosity (Paavilainen 2000; Sung *et al.* 2015).
- Cellulose, hemicelluloses, and lignin content: The proportions of these three chemical components in the fibers will affect the degree of fiber bonding and product stiffness in the case of thermally cured FMPPs (Dislaire *et al.* 2021a,b; Curling *et al.* 2017).
- pH: An important feature when using waste paper for FMPPs production is the possibility of CaCO_3 dissolving (machinery scaling) and CO_2 being released from it (fibrous slurry foaming) in the event of “meeting” of waste paper pulp sized in an acidic environment with waste paper pulp containing CaCO_3 in pulp/machine chests (Debnath *et al.* 2022).
- Susceptibility to shrinkage and tendency to development of waves, wrinkles, or other defects during drying.

Additional Materials Used in FMPP Production

Chemical agents are added to the fiber suspension during FMPPs production for a variety of reasons, including the following:

- Prevent difficulties occurring at the stage of forming FMPPs from a fibrous slurry,
- Improve the quality of these products,
- Give them the properties of plastic products (very high water resistance, appearance, very smooth surface, possibility of cleaning from dirt).

Chemicals that prevent production difficulties include those:

- Preventing wet FMPP from sticking to the surface of the forming and transferring matrices [(release agents, *e.g.*, poly(dimethylsiloxane) and magnesium or calcium stearate emulsions] (Debnath *et al.* 2022).
- Preventing excessive flocculation of fibers (pH regulators, *e.g.*, aluminium sulfate) (Sung *et al.* 2015; Semple *et al.* 2022).
- Increasing the wet strength of FMPPs (polyamidoamine-epichlorohydrin resins, crosslinked glyoxylated polyacrylamide (GPAM) (Debnath *et al.* 2022; Quin *et al.* 2022).
- Improving the drainage of the suspension of pulp on the sieve and retention of fine particles [(papermaking flocculants: aluminum sulfate, polyethylene imine (PEI), polyacrylamides (PAM)] (Debnath *et al.* 2022).
- Defoaming agents (Pelton 1989; Debnath *et al.* 2022).

In turn, the chemical agents that have a demonstrated ability to improve the quality of the finished product include those:

- Facilitating the production of a smooth product with well-shaped edges [(*e.g.*, starch, polyvinyl alcohol (PVOH)) (DAIHO 2025).
- Increasing the strength of the finished product in a wet and dry state [(*e.g.*, PVOH, modified chitosan, enzymatic lignin (EHL), polyamide epichlorohydrin (PAE)/cationic starch mixture, and plant proteins) (Noguchi *et al.* 1997; Hamzeh *et al.* 2013; Waranyou 2014; Hubbe and Gill 2016; Debnath *et al.* 2022; Quin *et al.* 2022; Zhao *et al.* 2020).

- Giving them barrier properties in relation to water, oil, fats, oxygen, and water vapor [rosin sizes, alkyl ketene dimer (AKD) sizes, alkenyl succinic anhydride (ASA) sizes, waxes (Kucherer 1995; Hubbe 2006; Waranyou 2014; Sung *et al.* 2015; Liu *et al.* 2021; Debnath *et al.* 2022), thin layer of a film made of polyethylene terephthalate (PET) or polyethylene (PE) (Semple *et al.* 2022; Triantafillopoulos and Koukoulas 2020).
- Increasing their resistance to oils and fats (*e.g.*, fluorocarbons) (Yang *et al.* 1999; Debnath *et al.* 2022).
- Improving the aesthetics of the product (dyes).
- Giving them better resistance to flaking/linting (cellulose nanofibers, mixture of microfibrillated cellulose and anionic starch) (Balea *et al.* 2018; Song *et al.* 2010).
- Deactivating microbes and fungi (probably standard papermaking chemicals used for this aim).

In the past, special processes were used to surface-finish FMPPs to give them superhydrophobic and oleophobic properties and make them similar to plastic products, *e.g.*, by impregnating, leveling, priming, and finishing with various substances. These properties of FMPPs are important for such products as buckets, bowls, basins, tubs, pails, tubs, *etc.*, which are probably not currently produced using the FM method, although they were produced using it in the past.

Of the impregnating or binding substances that were used in the past, one can mention the following (Palenik 1954; Stierlingov 1961):

- A mixture of coumarone resin with tall oil and manganese-lead siccative.
- A mixture of linseed oil, esterified colophony, glycerol, lead litharge, phthalic anhydride, and phenol-formaldehyde resin, and white spirit.
- Linseed oil or a mixture of drying oils.
- Thermoplastic dispersions of synthetic resins (butadiene-styrene polymer, polyvinylidene chloride, polybutadiene, butadiene copolymer with acrylic acid nitrile).

FMPPs surface leveling agents were mainly putties prepared by mixing together the following kinds of substances:

- Titanium white, talc, linseed oil or nitrocellulose varnish, plasticizer, and thinner.
- Zinc white and alkyd varnish.
- Zinc white, chalk (CaCO_3), varnish, and solvent.
- Phenol-formaldehyde resins (Carlson and Horowitz 1960).

In turn, the substances used to prime the surface of the finished product were (Palenik 1954; Stierlingov 1961):

- Nitrocellulose primers.
- Oil primers.
- A mixture of zinc white (ZnO), glyptal varnish, white spirit, and ochre.
- A mixture of alkyd resin and wood oil.

For the final finishing of FMPP surfaces, the following varnishes were used (Palenik 1954; Stierlingov 1961) based on:

- Nitrocellulose.
- Oil.
- Glyptal.
- Copal.

The method of using these substances to give FMPPs permanent water resistance and make them similar to plastic products is shown in Fig. 3. This figure shows that impregnating, leveling, priming, and finishing substances were introduced into FMPPs by immersion (1) of FMPPs in their solution and by spraying the surface of these products with appropriate solution (2, 3).

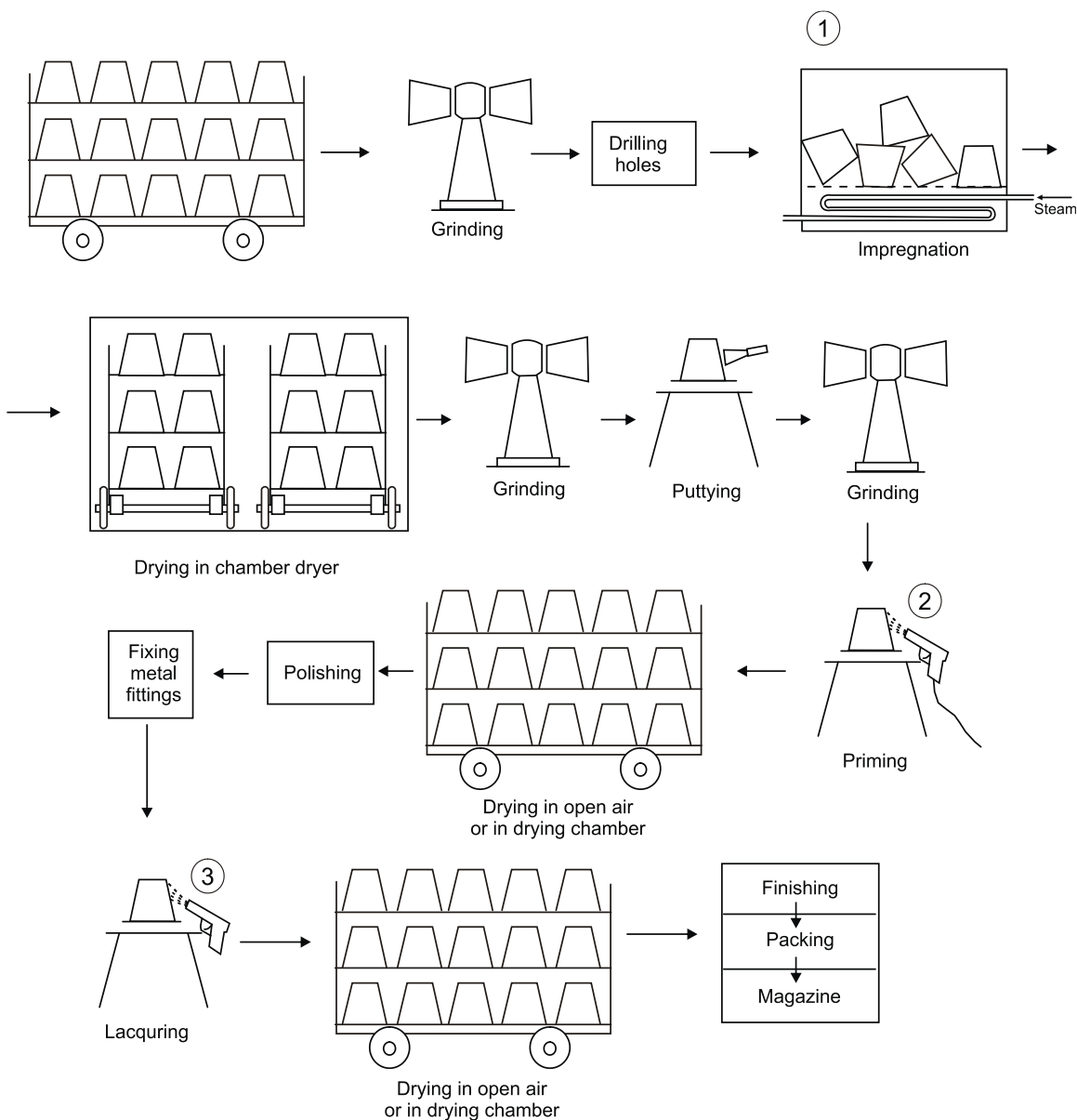


Fig. 3. Production line of fiber-pulp buckets after their formation, including chemical operations (impregnation, filling, priming, varnishing) and mechanical operations (grinding, polishing)

The use of the above-mentioned substances for finishing FMPPs was written about in the 1950s. As it was mentioned, in recent literature on the subject, there is no data on the mass production bowls, basins, tubs, buckets, pails, and tubs that are very resistant to water from papermaking pulps using the FM method. It is probable that the production of these products was abandoned as a result of their production of plastics from the 1970s. Any resumption of production of this type of product would require the development of

alternative methods of protecting them from water and oil absorption using chemicals that would be fully biodegradable and harmless to human health, which is no small challenge.

CATEGORIES OF FMPPS PRODUCED AND THEIR PROPERTIES

The pulp products made using the FM method in commercial facilities are usually divided into four classes, taking into consideration the quality of their walls and edges (Su *et al.* 2018; Disclaire *et al.* 2021b; Pulp-tec 2025). In this article, the FMPPs will be divided into two main groups, *i.e.*, *soft molded pulp products* and *hard molded pulp products*, according to the suggestion of Emery and Emery (1963), which were in first case divided into *thick-walled* and *transfer-pressed* products, but in the second one into *strongly wet-pressed*, *thermoformed*, *injection molded* pulp products. The last category proposed is *processed* FMPPs, which includes soft and hard molded pulp products that have undergone refinement.

Soft Molded Pulp Products

The soft molded pulp products can be categorized as follows:

Thick-walled products

Thick-walled products (one-sided smoothed) with 5 to 10 mm thick walls are produced as a result of depositing fibers on a row of sieve molds immersed in a fibrous suspension under the action of a vacuum and then drying the obtained pulp product under the sun or in a chamber air dryer, without pressing the reverse side of the product after it is removed from the bulk vat between these two production stages. For this reason, they are characterized by a moderately smooth surface on the side of the sieve form, while the opposite surface is unfinished and even rough. The products are used to protect various fragile and heavy products against mechanical damage during transport from the factory to the customer, for which neither a high-quality surface finish nor a perfect fit to the shape of the product is required (*e.g.*, egg shells, fruit trays, two-piece containers, shock-absorbing inserts for cardboard boxes replacing EPS inserts, corners, and angle brackets). The scheme for the production of such products is shown in Fig. 4 (Dey *et al.* 2020; Sengupta *et al.* 2022; Zhang *et al.* 2022; Singh *et al.* 2023; Pulp-tec 2025) (*e.g.*, eggshells, fruit trays, two-piece containers, shock-absorbing inserts for cardboard boxes replacing EPS inserts, corners, angle brackets).

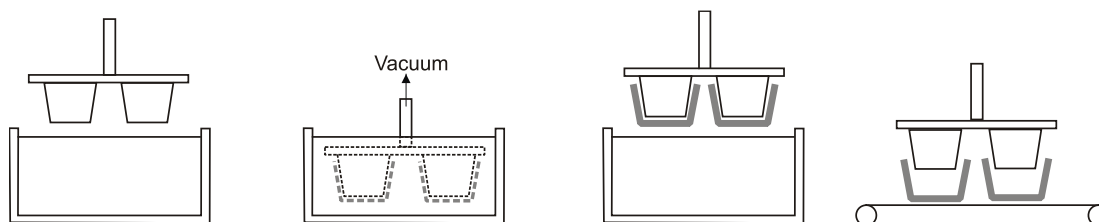


Fig. 4. Schematic representation of the *thickwalled* FMPP production

Transfer-pressed products

Transfer-pressed products (double-sided smoothed) have thinner walls (in most cases 3 to 5 mm) than the previous category. They are manufactured similarly to *thick-walled* products using additional transferring operation of the fibrous product after their

forming with pressing to the transfer mold to smooth its inverse rough surface (Fig. 5). This smoothing occurs by pressing action between the forming and transferring forms. The smaller wall thickness of the *transfer-pressed* pulp products, as well as the covering of the production form (PF) with a sieve of very fine mesh, gives the relatively smooth surface of both sides of the product better dimensional stability and improves its aesthetic properties. The main applications of this type of FMPPs are the protection of eggs and electronic equipment (Didone *et al.* 2017; Dey *et al.* 2020; Zhang *et al.* 2022; Pulp-tec 2025).

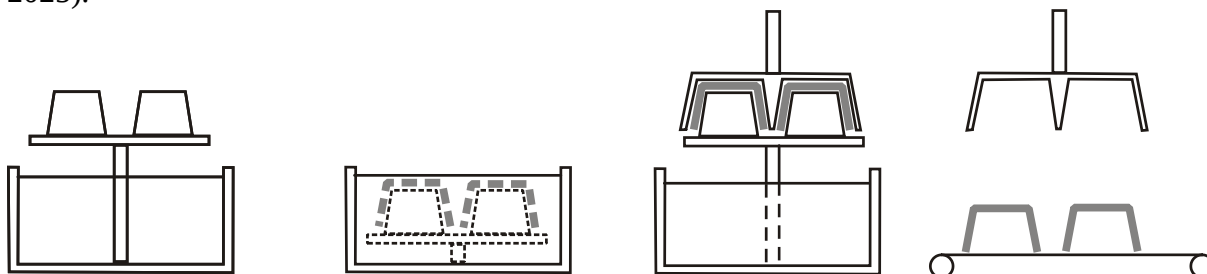


Fig. 5. Schematic representation of the *transfer-pressed* FMPP production

An additional increase in the surface smoothness of the *thickwalled* and *transfer-pressed* FMPPs can be obtained by subjecting it to additional ironing after drying in a special metal form, the main purpose of which is calibration of their dimensions (Pulp-tec 2025).

Hard Molded Pulp Products

Strongly wet-pressed FMPPS

The variant of the vacuum technique that also enables obtaining two-sided smooth products is the technique of production of *strongly wet-pressed* FMPPs (Fig. 6). Data on the production of such products (for example, buckets with a capacity of 10 liters, larger bowls, *etc.*) come from the 1960s (Sterlingov 1961, Emery and Emery 1966). It is not known whether this type of device is still used. The technique of producing deep, *strongly wet-pressed* pulp products, two-sided smooth, characterizes by unity, the higher pressures used to compress FMPPs in wet state, and the design of the forming device. This is due to the greater susceptibility of deep fibrous pulp products to damage in the wet state during their transfer to the dryer and the need to obtain greater dry strength of the product thanks to its higher density.

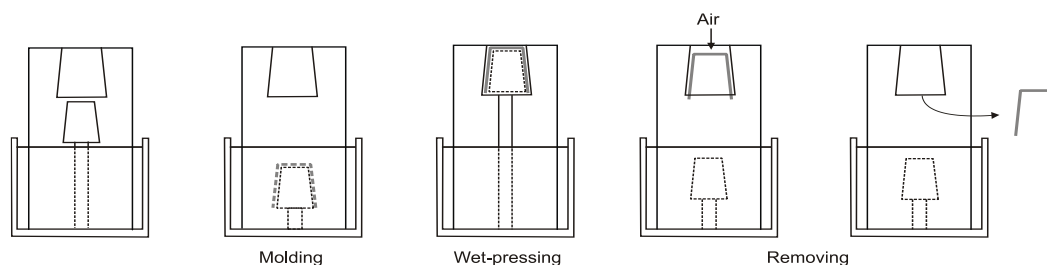


Fig. 6. Schematic representation of the *strongly wet-pressed* FMPPs production

Sterlingov (1961) reports that this type of technique was used to produce barrels, buckets, speaker membranes, balalaika and guitar cases, car parts, and the bodies of travel suitcases.

Thermoformed FMPPs

Thermoformed FMPPs (super double-sided smooth) have a wall thickness of 2 to 4 mm. Manufacturing of these category of FMPPs takes place in special devices in which the formed product is pressed in a multiple heated molds for a certain period of time between two tightly closed forms at a temperature of 140 to 220 °C, where its structure is highly thickened and dried (Fig. 7) (Huang *et al.* 2009; Didone and Tosello 2019; Semple *et al.* 2022). This technique of making pulp products makes it possible to obtain products with low basis weight, having high geometrical accuracy and smooth inner and outer surfaces that enables the converter to print their surfaces (Casey 1961; Pulp-tec 2025; Dislaire *et al.* 2021a,b). Nevertheless, the thermoforming of molded pulp is an energy-intensive operation, and a research effort is needed in this direction for making the process more sustainable in terms energetic efficiency (Didone and Tosello 2019). Studies have shown that the quality of *thermoformed* FMPP products (strength, flexibility, porosity, water absorption) may be influenced not only by the pressing temperature, time, and pressure, but also by the addition of binders to the pulp slurry before thermoforming (*e.g.*, wax, starch) and by the content of cellulose, lignin, and hemicelluloses in pulp (Wang *et al.* 2019; Wang *et al.* 2021; Dislaire *et al.* 2021b; Semple *et al.* 2022; Ruwoldt and Tanase Opedal 2022; Pasquier *et al.* 2023) due to different softening temperatures of these components and binding properties (Back and Salmen 1982).

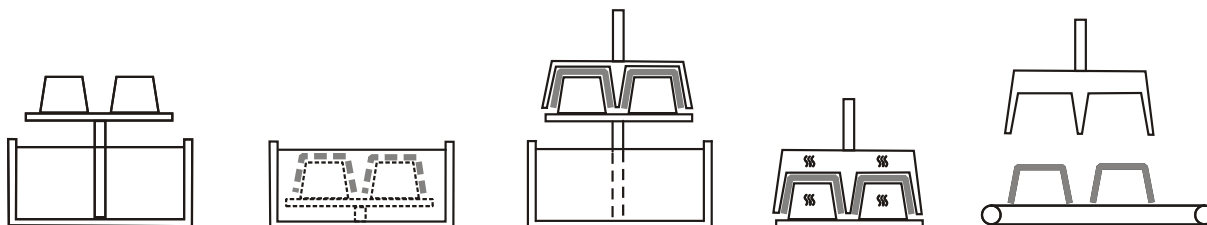


Fig. 7. Schematic representation of the *thermoformed* FMPPs production (Pulp-tec 2025) (author's drawing)

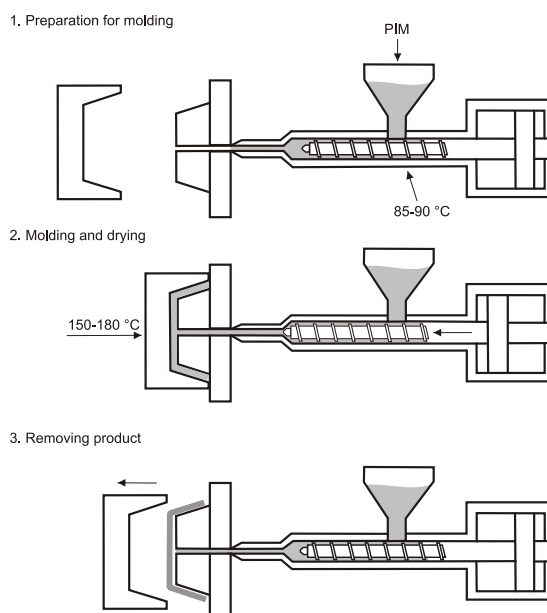


Fig. 8. The principle of manufacturing of the *injection-molded* FMPPs

Injection-molded FMPPs

This technique is used for production of FMPPs with thin walls, super smooth surfaces, very well-formed edges, multi-rib structures, hinge shapes, and microshapes. Such features are obtained through injecting a fiber suspension mixed with other additives into the form in a device similar to one used in manufacturing thermoplastic polymer consisting of the charging cylinder, mold, mold closing mechanism, injection mechanism, cooling system, and FMPPs ejection mechanism (Rabbi *et al.* 2021). This technology makes it possible to obtain FMPPs not only with well-formed edges but also, in many cases with complex shapes, which until now could be made only using thermoplastic polymer molding technology. The principle of production of this type of product is shown in Fig. 8 (DAIHO 2025).

Processed Molded Pulp Products

This type refers to soft molded and hard molded FMPPs that require some type of special secondary treatment other than simply being molded and dried, such as, printing, hot-pressing, die-cutting, trimming, manufacturing using colors or special slurry additives, but also a coating and impregnating carried out by spraying and immersion methods. This process may be used for applications that require a specific finishing of the surface of FMPPs (*e.g.*, barrier properties) that cannot be obtained by the pulp product alone (Palenik 1954; Dey *et al.* 2020; Dislaire *et al.* 2021b).

PROPERTIES

One of the main applications of FMPPs currently is to protect industrial and agricultural products from damage during transport. In such applications, the density of FMPP walls, their compression resistance, the ability to absorb shock (cushioning properties), bending stiffness, and thermoinsulating properties of these products will be of the greatest importance (Didone *et al.* 2017; Potaszew *et al.* 2019; Liu *et al.* 2023). These properties will be mainly influenced by the kind of fibers used to produce FMPPs, the degree of pulp beating, their form (single-chamber, multi-chamber products), the shape of their cell(s) [(rib, bucket, sidestep, composite structure, cone, wedge, stairs, pyramid, prism, hemisphere, *etc.* (Ma *et al.* 2004; Wang *et al.* 2012)], their wall thicknesses and angles of inclination, the area of their wall connections, and the production technique.

The density of FMPP walls has an influence on the strength properties of these products and determines their application. For example, packaging of large and heavy items or collection packaging requires high strength of FMPPs and therefore higher density. It will depend on the kind of pulp (virgin/recycled), the degree of their beating, and the manufacturing technique. The less long fibers FMPPs contains, the more the pulp used for its production is beaten, and the higher the forming pressure and temperature, the higher the density of FMPP walls. It is said that FMPPs produced traditionally, by single-suction technique (*thick-walled*) have typically densities in the range 0.22 to 0.35 g/cm³, and in those obtained by the hot-pressing technique their density can increase to even 0.8 to 1.1 g/cm³ (Didone *et al.* 2017; Wang *et al.* 2018; Dey *et al.* 2021).

The compression resistance of FMPPs is determined usually by analyzing the compression curves of these products obtained under static or dynamic conditions. These curves allow for comparing the compressive strength of different FMPPs between each other and with the behavior of products whose main functions are similar, *e.g.*, EPS,

paperboard, *etc.* (Eagleton and Marcondes 1994; Hoffmann 2000; Noguchi *et al.* 1997; Gurav *et al.* 2003; Ma *et al.* 2004; Ji and Wang 2011; Didone *et al.* 2017; Debnath *et al.* 2022). For example, it has been found that the compressive stress/strength of molded pulp in static conditions improves with increasing its density (Didone *et al.* 2017). It was also established that the compressive load of FMPP structures should improve with the increase in thickness of their walls and decrease with the increase in wall slope angle and fillet radius (cone-type structure) and height (in the case of pyramid-type structure) (Ma *et al.* 2004). The shape of FMPPs may have a significant influence on their crushing strength (a truncated cone has 20% better compression strength than a rectangular or squared geometry) (Hoffmann 2000). Sørensen and Hooffman (2003) noted that an increase in humidity from 50% r.h. to 95% r.h. at constant temperature results in a drastic reduction in % static compression strength of FMPPs from 100% to 40%, whereas the temperature effect is typically less than 10% SCS when reducing temperature from 25°C to 2 °C.

Cushioning properties of FMPPs can be determined using ASTM method D1596 (Didone *et al.* 2017). The method is used to determine the shock-absorbing characteristics by analyzing dynamic cushioning curves. It is done by placing an unrestrained package cushioning sample on a rigid surface and shocking it with a metal platen of known weight. This characteristic is obtained thanks to the possibility of measuring the mechanical shock experienced by such platen as it impacts the test sample falling on it from a certain height. The effect is quantified by an accelerometer mounted on the top of it, which is connected with a data acquisition device (QF 2025).

Research concerning the shock-absorbing ability of FMPPs showed, for example, that round-shaped FMPPs have better cushion strength than those having a rectangular shape because the latter tear along the oblique edges, and then the four sides collapse. The round type FMPPs deform gradually, like a concertina, starting from the top due to the decreasing circumference from the bottom to the top of the cone (Hoffmann 2000). Another finding in the area was the statement that mixing the pulp with plastic microspheres and starch powder improves the shock-absorbing properties of FMPPs (Noguchi *et al.* 1997).

A promising research direction in the field of buffer and cushioning performance of FMPPs is the prediction of deformation characteristics of the product based on computer modeling (Gurav *et al.* 2003; Wang *et al.* 2012; Wang *et al.* 2014; Xin *et al.* 2014; Didone *et al.* 2017). According to Ma *et al.* (2004) and Potashiev *et al.* (2019), for the successful application of this approach, it is necessary to collect data from different sources and construct a global database that has the ability to provide valuable guidance and a library on the loading performances of different structural units in order to give a design capacity.

In the case of some FMPPs, *e.g.*, plates, cups, bottles, lunch boxes, speaker cones, CD cases, large container packaging, planters, and others, in addition to density, compression, and cushioning strength, other paper properties, such as breaking strength, tear and *burst resistance in wet and dry states* (*e.g.*, form-molded coffee cups), elongation at break (Buxoo and Jeetah 2020), *bending stiffness* (Wang *et al.* 2018), surface smoothness (Han 2022), dimensional stability, printability, and resistance to low or elevated temperatures may also be important. Such properties will be significantly influenced by the type of fibrous pulp (Disclaire *et al.* 2021a; Oliaeli *et al.* 2021a; Pasquier *et al.* 2024), its preparation for this production (degree of beating, additional delignification) (Debnath *et al.* 2022; Wang *et al.* 2018), the conditions of the production process (Pasquier *et al.* 2023), and the chemical additives used (Quin *et al.* 2022; Ruwoldt and Tanase Opedal 2022; Debnath *et al.* 2022;).

For example, it is commonly known in papermaking that:

- Chemical pulps (kraft, sulfite) have higher tensile strength after beating than mechanical pulps.
- On the other hand, mechanical pulps at certain basis weight of paper give higher bulk (lower density) than chemical pulps,
- Kraft pulps should show better strength properties than sulfite pulps and waste paper pulps.
- Softwood pulps give higher tear index than hardwood pulps, but on the other hand, the latter pulps give better surface/printing properties than the former.
- Chemical straw pulps give denser and stiffer paper than chemical pulps from wood, while mechanical pulps give bulkier and stiffer paper than chemical pulps.
- Pulps from bast fibers and cotton fibers may be characterized by lower tensile strength than kraft and sulfite pulps from wood.

So, by selecting the appropriate fibrous intermediate, it is possible to significantly influence the strength and surface properties of FMPPs.

Wang *et al.* (2018) showed that when the content of lignin in high-yield soda-AQ pulp was decreased from 24.9% to 11.45% as a result of partial delignification, the density of FMPP increased by 6.0%, the tensile strength increased by 22.0%, and the bending strength increased by 23.9%. Later, they also showed that when the fibers of CTMP poplar pulp were treated by a chemical etching process to selectively remove surface lignin, internal lignin, and hemicelluloses, the cell wall plasticity could be tuned by controlling the fiber moisture content during the compression molding process, which resulted in the increase in fiber plasticity. As a result improvement, the tensile strength and the flexural strength of thermoformed FMPPs increased from 38.0 to 83.5 MPa and from 31.2 to 73.3 MPa, respectively (Wang *et al.* 2019).

The tensile strength of thickwalled FMPPs was studied by Gurav *et al.* (2003). These researchers found a high coefficient of variation of maximum loading in tensile strength tests, which was much higher than the coefficient of variation of specific weight and wall thickness of FMPPs. So, these variations in this property could be attributed to the geometrical discontinuities and presence of impurities, for example, of waste paper origin.

The strength properties of FMPPs can also be modified to a large extent by the degree of beating of the fibrous intermediate. Paper's tensile strength is known to increase as a result of increased flexibility of the fibers, their external fibrillation, and increased content of the fine fraction in the pulp. However, beating papermaking pulps increases the costs of producing FMPPs and their density, which may be unfavorable from the point of view of the transport costs of these products. Therefore, a desirable solution would be to obtain the required tensile strength of FMPPs without beating the fibrous intermediate or with its minimal beating. This type of effect was obtained by Rice *et al.* (2018). They found that nanofibrillated cellulose (NFC) that had been pretreated with cationic starch at a high level was especially effective at boosting the tensile strength and stiffness of sheets prepared from pulp that had been refined at a low level, thus achieving improved strength at relatively low apparent density (high bulk) of the handsheets. As for nanocellulose, Han (2022) applied it to the surface of lunch boxes and found a flatter and more uniform surface of these boxes than conventional ones, as well as a greater resistance to deformation of the former.

One of the most well-known substances that can be used to improve the tensile strength of FMPPs is starch. For example, Howar and Jowsey (1989) and Sandak *et al.*

(2015) reported lately that the addition of cationic starch (CS) improved the mechanical properties of paper, which could be used in the case of FMPPs. Quin *et al.* (2022) obtained FMPPs that had a high dry strength of 24.4 kN/m, and wet strength of 4.22 kN/m using the addition of polyaminoamide-epichlorohydrin resin (PAE) and CS at contents of 1.0% and 0.6%, respectively. The positive effect of PAE use on the dry and wet tensile index of paper was also shown by Su *et al.* (2012).

Lignin also exhibits binding properties towards plant fibers. Oliaeli *et al.* (2021b), for example, found that it can bind them relatively strongly and increase the tensile strength of paper products made from pulps containing a lot of this component in the fibers. This is due to the thermoplastic properties of lignin, which, when subjected to thermal treatment, melts and acts as a filler, binder, and hydrophobic agent, endowing, for example, the pulp lunchboxes, with a high mechanical strength of, *e.g.*, 44 MPa, stiffness of 12.9 mN·m, sustained wet support strength for over 30 days, and excellent wet stability (Wang *et al.* 2021). Pasquier *et al.* (2023) reached a similar conclusion regarding the effect of lignin content on the tensile strength of FMPPs, stating that CTMP pulp containing more lignin than kraft pulp exhibits an optimum in terms of tensile strength at intermediate thermoforming pressure. Similarly, Zhao *et al.* (2020) reported the possibility of adding enzymatic hydrolysis lignin (EHL) to increase the tensile strength of FMPPs up to 20.3 MPa by expanding the contact area between the EHL and fibers reducing the holes between fibers.

The tensile strength of FMPPs could also be practically significantly improved by adding holocellulose pulp (Yang *et al.* 2019). The problem in this case, however, is that such pulp is not available industrially.

When introducing additional chemical substances into the structure of FMPPs, it should be taken into account that the presence of these substances may adversely affect various properties of the product packaged in FMPPs, including especially food in the event of their contact with the surface of this product or migration into its interior.

The essential properties of FMPPs are their water and oil resistance from the group of barrier properties. Traditional methods of obtaining such properties in papermaking are, as mentioned above, in the first case, the use of rosin (from softwoods), AKD and ASA sizing agents, and in the second case, the strong mechanical refining of the pulp and the use of fluorocarbon preparations, as well as coating such products with foil, *e.g.*, polyethylene, which allows obtaining both water and grease resistance.

However, the disadvantages of these agents [(*e.g.*, low pH of rosin size application, high energy consumption for pulp beating, harmfulness of the decomposition products of fluorinated carbon compounds (Sheng *et al.* 2019), lack of biodegradability and compostability of *e.g.*, polyethylene)] mean that new methods of imparting these features to FMPPs that do not exhibit such defects are sought, especially those intended for use in contact with food.

So far, a relatively large number of these substances have been tested to impart barrier properties to different types of paper products. For example, Triantafillopoulos and Koukoulas (2020) presented many existing possibilities of obtaining barrier properties using biodegradable and compostable biofilms containing polylactide acid (PLA), polyhydroxyalkanoates (PHA), thermoplastic starch (TPS), and blends of these materials. Ahuja *et al.* (2022) further present the achievements in the field of PLA and PHA applications, indicating the possibility of achieving significant improvement in the barrier properties (increase of the shelf life of the food product) of these biopolymers using nanomaterials in the polymer bulk or by coating them with a barrier layer. These

nanomaterials include nanocrystalline cellulose (CNC), cellulose nanofibril (CNF, also called nanofibrillated cellulose), cellulose nanosphere (CNS), nanocrystalline cellulose-nano silver (CNC-Ag), hydrogenated carbon (HC), organomodified montmorillonite nanoclay (MMT), surfactant modified montmorillonite nanoclay (sMMT), and ZnO nanoparticles (ZnO).

Nair *et al.* (2023) presented methods of imparting barrier properties to packaging with various types of substances of natural origin. According to these authors, methylcellulose, and hydroxypropyl cellulose films are very efficient barriers to O₂, CO₂, and lipids, but they have a low resistance to water vapor transfer. However, the water vapor barrier characteristics can be increased by including hydrophobic elements such as lipids in the film-forming solution. Cellulose acetate film is also an approved biofilm for food packaging.

Chitosan has similar properties to methylcellulose. It can be used relatively easily to produce coatings, but like methylcellulose, it is not very waterproof, and chitosan itself is not thermoplastic (it degrades before reaching the melting point). Therefore, chitosan is difficult to extrude, and the films cannot be heat-sealed, which limits their production at the commercial level. However, chitosan can be modified by changing solvent type, pH, adding plasticizers, and incorporating lipid components, which improves its properties (Gällstedt and Hedenquist 2006; Cázon *et al.* 2017; Xie *et al.* 2022; Nair *et al.* 2023).

Alginates also have film-forming properties. Pure alginate biofilms are not waterproof. However, if alginates are cross-linked with Ca²⁺ ions (Zhang *et al.* 2017; Nair *et al.* 2023) or prepared in mixtures with sodium carboxymethyl cellulose or propylene glycol alginate, their barrier properties against water and water and oil are significantly improved. Protein-related substances that can be used to impart barrier properties to FMPPs are milk proteins, such as caseinates (sodium caseinate, calcium caseinate), whey protein isolates (WPI), isolated soy proteins (ISP), zein corn protein, and prolamin protein present in corn. For example, Han and Krochta (2006) reported that WPI coating significantly reduced oil contact angle on paper associated with oil absorption by paper and WPI coating improved packaging material performance of paper, by increasing oil resistance without significant change in optical and mechanical properties. Similarly, Park *et al.* (2000) found that the grease resistance of papers coated with ISP at levels higher than 2.0 kg/ream was equal to that of polyethylene laminates used for quick-service restaurant sandwich packaging.

In turn, the zein-chitosan blend is appropriate to prevent moisture loss, make barriers, and ensure the prolonged shelf life of fruits (Pavlátková *et al.* 2023). Similarly, Trezza and Vergabo (1994) claim that there was no difference in grease resistance index (%AS. hr⁻¹) between 4.4 and 6.6 kg per ream of zein-coated paper and commercial polyethylene laminated paper. Other substances that could be classified as emerging in the category of those demonstrating the ability to produce water- and oil-impermeable coatings are crosslinked cellulose (*i.e.*, derivatives of cellulose made by esterification with either fatty carboxylic acid or fatty acid chlorides) (Ahuja *et al.* 2022); composites of nanofibrillated cellulose and O-acetyl-galacto-glucomannan (GGM) coated with succinic esters of GGM (Kisonen *et al.* 2015); films from NFC and chitosan nanoparticle (Hassan *et al.* 2016); and microfibrillated cellulose (cellulose microfibrils CMF) with the addition of CNC nano-lignocellulose subjected to hot-pressing (Rijal *et al.* 2023).

For example, Li *et al.* (2019) showed that hydrophobic CNF films can be prepared by the attachment of 10-undecylenoyl chloride onto CNFs. The films impenetrable with grease even at high temperatures were also obtained by Kisonen *et al.* (2015) by coating

nanofibrillated cellulose (NFC)–Norway spruce O-acetyl-galactoglucomannan (GGM) composite films with a novel succinic ester of GGM or with native GGM. Similarly, Hassan *et al.* (2016) reported that coating paper sheets with a thin film of nanofibrillated cellulose chitosan nanoparticles composite (NFC/CHNP) decreases porosity and water absorption and increases grease-proof properties of paper sheets, while Rijal *et al.* (2023) showed that the addition of CNC to the CMF substrate led to significant improvements in various membrane properties.

The number of possible alternative methods of obtaining FMPPs barrier properties using substances that are much more biodegradable than synthetic films is therefore large (certainly not all of them have been quoted here). Their use in industry will, however, depend on their resistance to decomposition during transport and storage, toxicity, resistance to reaction with food components or decomposition under their influence, degree of migration of these substances (*e.g.*, nano-sized chemicals) into food (issues revived by Semple *et al.* 2022), availability in the form of market products, price, ease of application, effectiveness of action, and biodegradability. The probability of their use in industrial practice certainly increases significantly if these methods were developed as part of a research project in which one of the partners was a manufacturing company.

The group of properties of FMPPs also includes their susceptibility to biodegradation. FMPPs produced only with the participation of plant fibers are fully biodegradable and compostable. So, determining the biodegradability and compostability of FMPPs makes sense when these products are produced with the use of agents that give them barrier properties in relation to water, oils, and gases and increase the degree of binding of their fibers (Muniyasamy *et al.* 2013). Studies of this type were carried out, for example, by Liu *et al.* (2020), Peng *et al.* (2007), and DAIHO (2025). They consist of placing FMPPs in a sample of unsterilized soil for 15 to 60 days under conditions of appropriate humidity and temperature and testing the number of grams of this product that did not decompose after a specified biodegradation time. Such studies are best performed before introducing FMPPs into industrial production in unit form. Therefore, in this context, the proposals to manufacture this type of product in unit laboratory production conditions are of great importance (Onilude *et al.* 2013; Gavazzo *et al.* 2008; Sikora and Danielewicz 2019; Saxena *et al.* 2020; Kalajo *et al.* 2021; Amono *et al.* 2022).

MANUFACTURING TECHNIQUES

Principle of Operation of Devices Used for Production of FMPPs

a) Vacuum-type devices

In these devices the factor causing the deposition of the fiber layer on the sieve form is vacuum. Among such devices used in the papermaking industry there were those working both continuously and periodically. Figures 9A and B show the principle of operation of rotary formers used for the production of *thick-walled* FMPPs colloquially known as carousels (Emery and Emery 1966; Głuszewski 1969).

The principle of operation of both formers is similar. From the storage tank, the fibrous slurry reaches the former pulp chest/tank (1), which is equipped with a regulating system that ensures a constant level of pulp slurry and the assumed fiber consistency. Above the chest, a rotary cylinder/drum is mounted (2) with PF installed in six rows (3). These forms are equipped with a system of regulation of the amount of vacuum and compressed air. When the forms are immersed in the chest below the level of fibrous slurry,

the negative pressure (400 to 600 mm Hg) sucks up the suspension located near the mold, which causes the fiber layer to settle on it and form the product wall, with the thickness depending on the time of immersion in the apparatus chest, the consistency of pulp slurry, and the amount of the vacuum. Then, the row of PF emerges from the chest, and the continuously acting vacuum sucks off the excess water from the fibers deposited on these forms, which become felted/molded and form the wall of the product (Stierlingov 1961; Głuszewski 1969; Martínez *et al.* 2016).

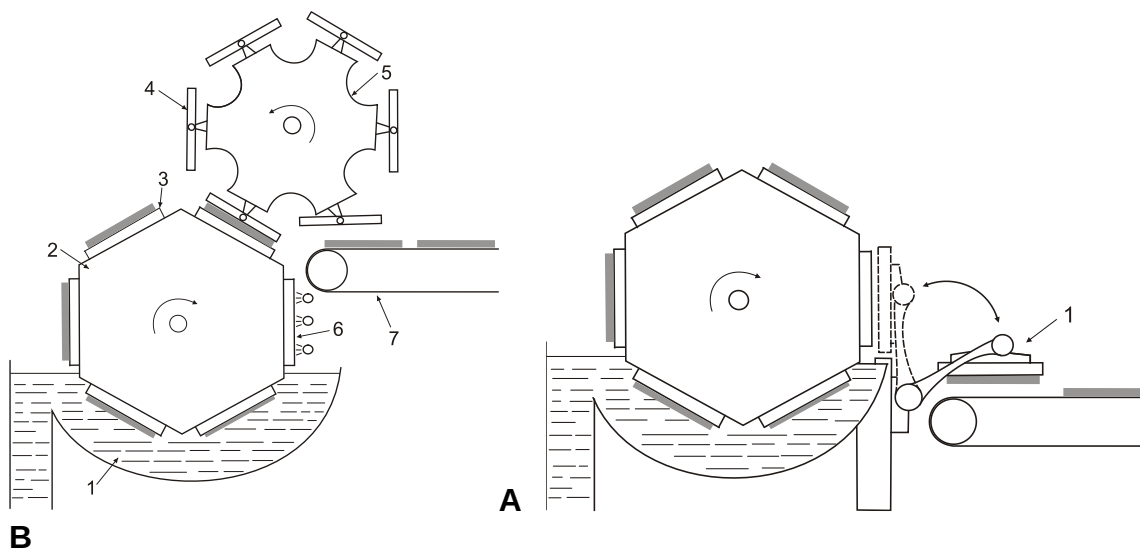


Fig. 9. Principle of operation of formers used for the production of *thick-walled* FMPPs, A – with a transfer drum, B – with a transfer frame (Głuszewski 1969) (author's drawing)

PFs are made by milling the shape of the product in a metal block and then drilling it in order to obtain the possibility of sucking the pulp slurry through the mold block. In addition, the form of the product is covered with a dense metal net (*e.g.*, 40 to 80 mesh), which ensures even distribution of fibers on the surface of the entire form. The most commonly used materials for making molds are aluminum, stainless steel, bronze, and special plastics. The material is selected in accordance with the planned production volume. Plastics are best suited for smaller production volumes, as molds are the cheapest to manufacture, while for very large quantity production, the forms are made from metal, preferably bronze, which is the most durable (Stierlingov 1961; Głuszewski 1969).

The fibrous products are then removed from the PFs by means of the suction transfer forms (4) mounted on a counter-rotating transfer drum (5) (Fig. 9A) or the transfer frame (1) (Fig. 9B). When the product is transferred from the PF to the transferring form the positive and negative pressure is activated in these forms, respectively, which pushes the pulp products towards the receiving forms which receives pulp product. To facilitate the removal of the pulp products from the PFs, they are sprayed with a solution of release agent (6), which prevents pulp products from sticking to the PFs. The receiving forms transfer pulp product on the belt conveyor (7), transporting them further to a chamber dryer for drying during from 10 to 15 min in temperature from 140 to 240 °C (Stierlingov 1961; Głuszewski 1969; Martínez *et al.* 2016).

The number of *thick-walled* FMPPs produced depends on the number of production molds installed on the rotary roller, the number of revolutions of this roller, the thickness of the fiber layer in the product, the vacuum value, the degree of process automation, the

drying speed, the speed of conveyors, and the efficiency of the equipment packaging the finished products. For example, it is reported that in the case of having 12 production molds, with the speed of the rotary roller rotation at 300 per hour, in 3 hours of work it is theoretically possible to produce 10,800 product units (Martínez *et al.* 2016).

Thick-walled products made using pulp FM were also manufactured using the unit method. An example of a device for manufacturing these products by this method is shown in Fig. 10 (Leman 1967). The device consisted of production unit and additional production parts. The production unit included an over-screen tank for collecting a specific volume of fibrous suspension (3), a sieve production mold (4), and an under-screen tank (5) for collecting water from the fibrous suspension draining, and connecting the vacuum (6). Additional devices included an overflow tank (1), and a tank for collecting pulp slurry (2).

The operating principle consisted of preparing the over-screen tank for operation, filling it with the pulp suspension, causing the fibers to settle on the sieve matrix by opening the valve (6), draining the FMPP-shaped pulp layer formed on the sieve with the help of a vacuum, removing it from the matrix, and sending it for drying in the drying chamber (Leman 1967). This technique could probably be used to form flat panels from fibrous pulp of various applications. The lack of a mechanical press does not exclude the possibility of pressing the obtained FMPP in another device to densify it.

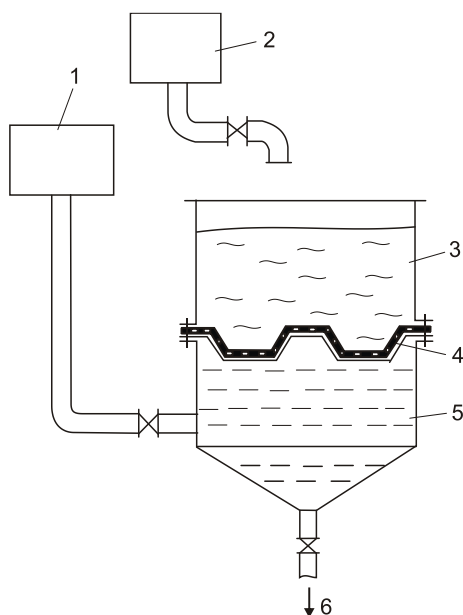


Fig. 10. Device for manufacturing probably of large recessed panels from fibrous pulp using the FM method (Leman 1967). 1 – overflow, 2 – a tank for collecting the supply of fibrous suspension, 3 – upper sieve part of the mold, 4 – sieve matrix, 5 – lower sieve part of the mold, 6 – negative pressure

Figure 11 shows the principle of operation of another type of vacuum device. This device is an example of application in industrial practice of *transfer-pressed* FMPPs production.

In the case of this device FMPPs are pressed before drying by transferring forms mounted on transferring drum (3) and then are removed from these forms by the forms of the drying chamber in which the produced FMPP are dried to prevents deformation of the

product due to shrinkage of its fibrous structure. The device has the chest with a pulp suspension (1), a shaft with rows of production forms (2) (in the figure for production paper plates), a drum with transferring forms which presses FMPP before drying it and smooths its underside, and a shaft with receiving forms (4), rotating in a drying chamber (5) into which hot air at 90 to 130 °C is injected. The use of drying of FMPPs on sieve forms in drying chamber is advantageous because it reduces the tendency of these products to undergo deformation (Stierlingov 1961).

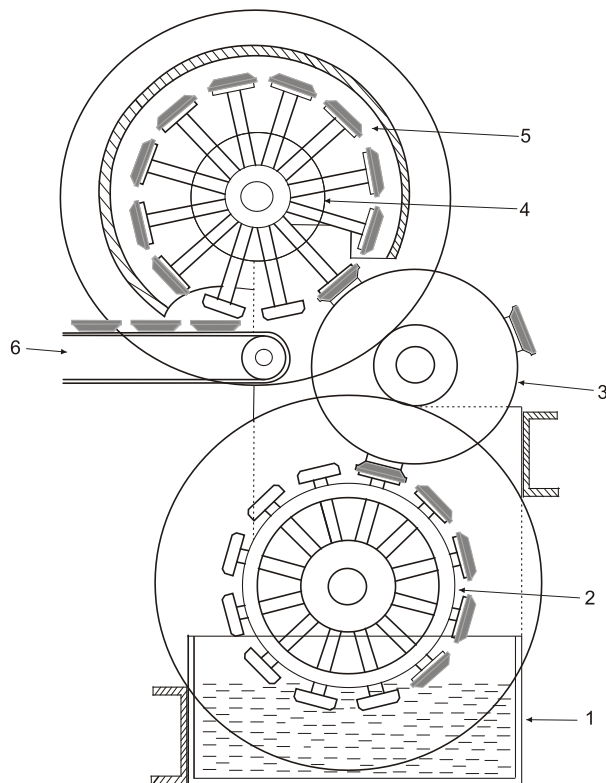


Fig. 11 Principle of operation of formers used for the production of *transfer mold* pulp products (Stierlingov 1961)

An additional improvement of the surface smoothness of *thick-walled* and *transfer-pressed* FMPPs dried in drying chambers without being placed in the forms can be obtained by subjecting them to so-called *calibration*, the main purpose of which is to restore the required shape to the pulp product, which can be deformed and shrunk during drying (Fig. 12). (Stierlingov 1961; AVP LCC 2018; QSheng 2018; Pulp-tec 2025).

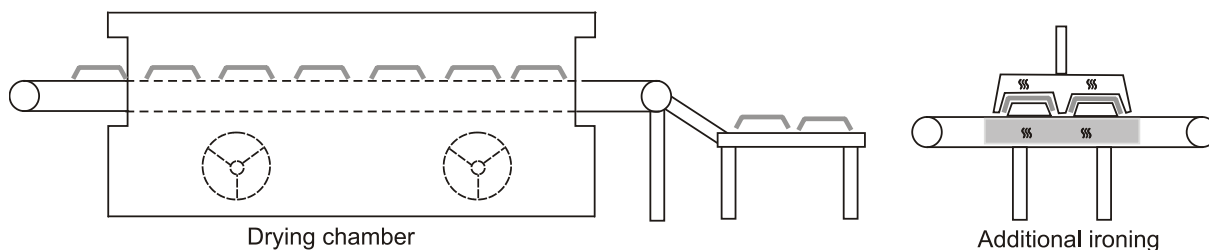


Fig. 12. Calibration of FMPPs after drying to recreate its desired shape (AVP LLC 2018)

The construction of a device for making deep, *strongly wet-pressed* pulp products from pulp is shown in Figs. 13A and B (Palenik 1954; Leman 1968; Głuchowski 1969).

The action of devices A and B is similar. As for devices A, it was a combination of a vat with fiber suspension (1), sieve form (2), hydraulic press (3), and counterform (4). The sieve form was attached to the end of the press piston. In the press piston housing, there was also a suction pipe (5) connected to a vacuum pump supplying negative pressure to the space under the sieve. The formation of buckets began after immersing the sieve form in the vat with pulp slurry. Due to negative pressure, fibers were deposited on the surface of the sieve. When the fiber layer on the sieve reached a suitable thickness (*e.g.*, 5–7 mm), the sieve form was lifted by the piston above the surface of the pulp suspension in the vat, which caused the fiber layer to compact on the screen due to its dehydration. Then the pulp product was pressed against the counterform, which caused a strong compression of the fibers on the sieve form and the formation of a compact fiber layer. The pressing pressure in this type of device could be as high as 150 atm. The counterform could be equipped with a heating system that can reach a temperature of 140 °C in order to increase the dryness of a product and density. After pressing, the sieve form with the pulp product was lowered down, and compressed air was introduced into it, which lifted the bucket slightly, allowing it to be removed from the sieve form without damage.

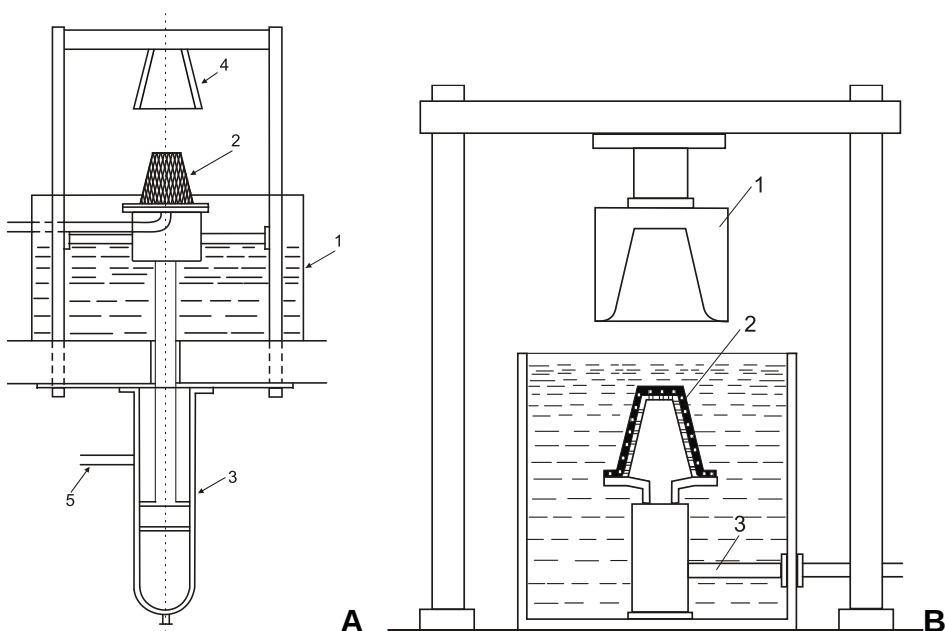


Fig. 13. Diagrams of the devices for manufacturing buckets from fiber pulp presented by Palenik (1954) (A) and Leman (1968) (B) (in the case of Fig. 13A: 1 – vat with pulp suspension, 2 – sieve matrix, 3 – servomotor of the press cylinder, 4 – counterform) i Lemana (1968) (1 – counterform, 2 – sieve mold, 3 – servomotor of the press cylinder with vacuum supply (author's drawing))

The obtained buckets were then placed on a multi-deck trolley, left to dry up for 2 to 3 hours at room temperature, and then dried in a dryer chamber for 48 to 72 hours at 45 to 50 °C to prevent deformation of the product (Fig. 14) (Palenik 1954). The dried buckets from pulp were then subjected to grinding (to remove unevenness of the surface), puttying in order to fill the recesses, drilling to make the holes for the metal fittings for handles, and then impregnation using the impregnation solutions of the composition mentioned earlier in this elaboration. Impregnation was carried out at elevated temperature, during the time

dependent on the required water resistance of the product. The impregnated products were then dried in a chamber dryer in which the impregnation was fixed. After this process, the product was leveled again through grinding, puttying, and grinding again. Then the undercoat was applied on the surface of the bucket. After drying, the bucket was polished, and the metal fittings were fixed to it. The last stages of the bucket from pulp production process were lacquering, drying, and final cleaning of the product (Fig. 3) (Palenik 1954; Głuchowski 1969).

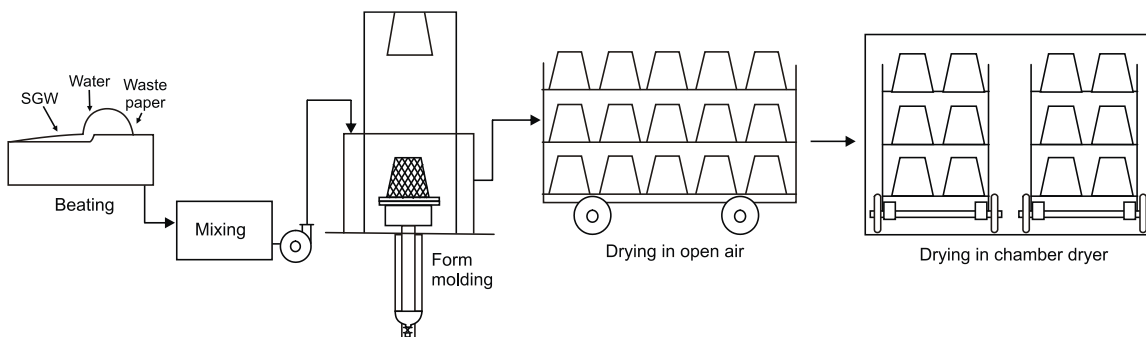


Fig. 14. Schematic diagram of the production of buckets from fibrous pulp using the FM devices shown in Fig. 13 (Palenik 1954) (author's drawing)

The conducted survey did not show that products such as buckets or bowls were manufactured on an industrial scale today. This task is not easy because, in the case of this type of product, it is necessary to obtain long-term water resistance, the aesthetically pleasing external appearance of the products, and their resistance to washing, which requires the availability of film-forming substances finishing their internal and external surfaces, which at the same time should be characterized by the least harmfulness to living organisms and the natural environment and the required modern biodegradability.

Another kind of device that utilizes vacuum for the production of FMPPs is presented in Fig. 15. It is used for manufacturing *thermoformed* pulp products. It differs from the production process of the previously discussed FMPPs by the use of its quick full drying in the same device in which it is formed (BeSure 2018).

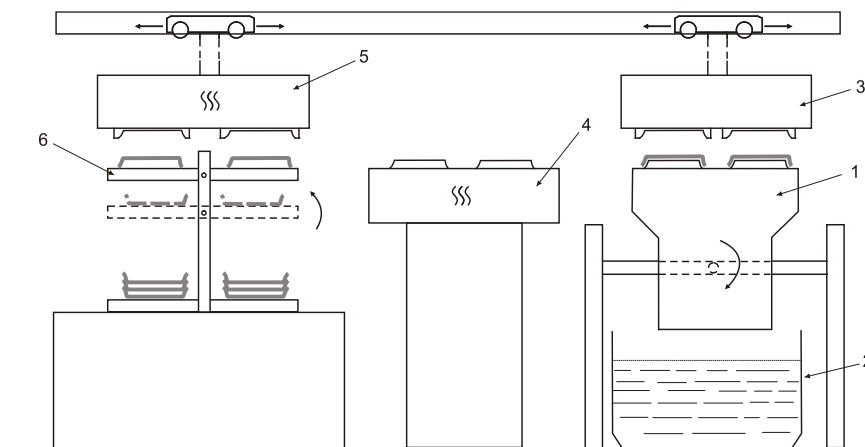


Fig. 15. The principle of operation of a device used for the production of *thermoformed* pulp products (BeSure 2018) (author's drawing)

In this device, the forming of pulp products (trays for small gastronomy) takes place on suction sieve forms installed on the rotary matrix (1), which is periodically immersed in a vat with pulp suspension (2). After getting the right amount of fiber on the forms, the matrix is turned upwards, after which the pulp products are removed from it by means of the receiving/transferring matrix (3). The matrix then transports the wet pulp trays horizontally to the central part of the device, where they are placed on the bottom part of the drying/pressing matrix (4). After placing the wet plates on this matrix, the receiving/transferring matrix returns to its original position, and the upper part of the drying/pressing matrix moves over these trays (5), which then, after descending, dries and compresses these products. After this process, the upper part of the pressing/drying matrix switches to suction mode, lifts up the trays, and then moves them aside above the stacking matrix (6), which stacks them into a stack (BeSure 2018).

b) Overpressure molding

Hydraulic molding: In this technique of production of FMPPs, the factor causing the deposition of the fiber layer on the sieve form is overpressure of pulp suspension (hydraulic molding) obtained by the force of the piston pressing on the fibrous pulp suspension, the force of compressed air pressure (pressurized air molding), or the force exerted on this suspension by the movement of the screw in the channel feeding it to the production mold (injection molding).

The data on the manufacture of the FMPPs through the hydraulic molding technique dates back to the 60s of the 20th century. The construction of these devices is shown in Fig. 16 (Stierlingov 1961).

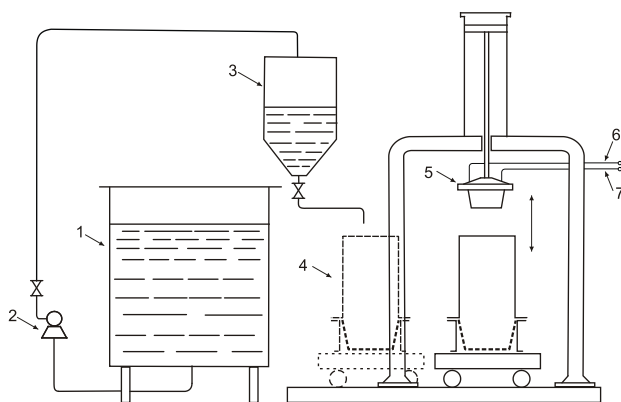


Fig. 16. The device for the production of FMPPs by the hydraulic molding (Stierlingov 1961)

The pulp slurry was fed from the pulp preparation vat (1) by means of a pump (2) to the pulp dispenser (3), from which it then flowed out into the sieve form chamber (4). This chamber was then placed in the working position in which a piston (5) of the shape of the product was introduced into them, hermetically closing it. This piston, exerting pressure on the fibrous slurry pole, caused water to pass through the sieve form, forming the product walls, and compressing them. Connection of the vacuum to piston (6) enabled removal of FMPP from the sieve chamber, while connection of hot air (7) to this piston enabled drying up the product (Stierlingov 1961).

Pressurized air molding: For the forming of these products, special automatic closing and opening sieve forms were used in which the deposition of fibers on the sieve

takes place due to the action of compressed air. A diagram of the device used for the production of FMPPs using compressed air molding is shown in Fig. 17.

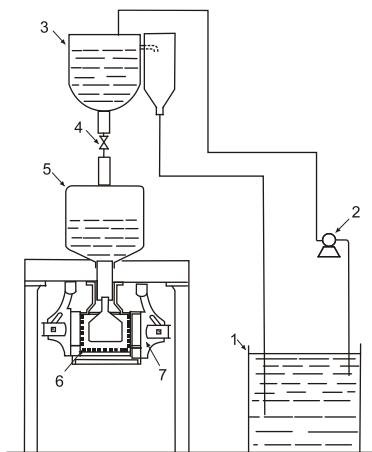


Fig. 17. Device for the production of containers and objects with walls arranged at right angles from fibrous pulp (Stierlingov 1961) (author's drawing)

A fibrous slurry was fed from the pulp preparation chest (1) by means of a pump (2) to the tank holding the pulp stock (3), from where it flowed to the dosing tank (5) through the valve (4). In the dosing tank, the consistency of the pulp suspension was regulated to 0.5 to 0.6%. Once the pulp consistency had been determined, the valve connecting the dosing tanks and the mixing tank with the stock of pulp suspension was closed, and air was introduced into the dosing tank (5) under the pressure of 0.5 to 4.0 atm. This resulted in the water from the pulp suspension starting to pass through the mesh of the sieve form (6), which caused the fibers to settle and to form the product wall. After passing the entire amount of pulp slurry through the walls of the molding form, hot air at a temperature of 300 to 400 °C was passed through it, which dried the pulp product. After some time, the hot air supply was automatically closed, and the form (7) was opened, after which the finished product was removed from the device (Stierlingov 1961).

The complete drying of products manufactured by this method could take place in sieve form by blowing the walls of the formed product with hot air. This drying method allows a completely dry product to be obtained without the disadvantages, such as bending and shrinkage of the product, which is important in the case of manufacturing products consisting of two parts, such as *e.g.* the jar. The disadvantage of this method of drying, however, is the reduction in the number of products made per time unit by 30 to 40%. Therefore, in practice, the majority of pulp products were pre-dried in the sieve form to 45% moisture content, followed by final drying in a chamber dryer at a temperature of 60 to 70 °C for 3 hours (Stierlingov 1961).

Water bottles are made up of polyethylene terephthalate and polypropylene. Most of them are only for single-use purposes, thus creating a massive amount of waste worldwide. Apart from water, bottles pack other liquids such as milk, shampoo, liquid soap, beverages (alcoholic, non-alcoholic, or carbonated), syrups (retail or pharmaceutical), and much more (Ahuja *et al.* 2022). The technology of producing paper bottles differs significantly from the production of PET bottles. In the latter, a so-called PET pre-form is first produced from this material using the thermoforming method, which is then softened using infrared radiation and stretched into a bottle in a second form using compressed air (YT 2025). A shift in packaging is necessary to move on to a more

sustainable approach to reducing plastic waste; hence, many producers of liquid products have started to work on paper bottles (Ahuja *et al.* 2022).

The production of containers for liquids from molded pulp, such as bottles and jars, can be considered a variant of the pressurized air molding in which pressurized air acts on fibrous slurry through a rubber balloon, which was patented by Kumamoto and Otani (2001) and Kumamoto *et al.* (2002). The first stage of producing, *e.g.*, a paper bottle is closing a two-part porous mold lined with a mesh on the inside. After this stage, a suspension of pulp is fed to the mold, and a vacuum is activated, which removes water outside the mold, leaving a layer of molded fibers on the mold surface (Fig. 18A). The next stage of the process of producing this type of container is to move the mold apart, remove the paper bottle from the pulp, and transfer it to a drying mold (Fig. 18B), also consisting of two parts. After closing it, an inflatable rubber element is introduced into its center, which is filled with hot air. Additionally, the drying process is supported by the vacuum and pressure action of the rubber element (Fig. 18C), which also prevents the walls of the container from shrinking (Didone *et al.* 2017; Saxena *et al.* 2019; Saxena and Bissacco 2016).

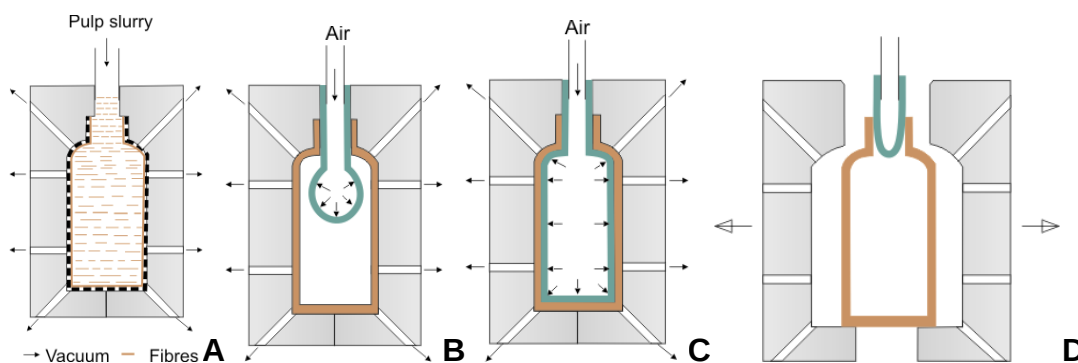


Fig. 18. Forming and drying of FMPP type container (bottle) using rubber membrane filled with hot air. A – insertion of inflatable rubber element, B – filling of inflatable rubber element with hot air and drying of bottle made of fiber pulp from the inside, C – opening of mold and removal of inflatable rubber element from the bottle (Didone *et al.* 2017; Saxena *et al.* 2019; Saxena and Bissacco 2016) (author's drawing)

After drying the product, the inflatable rubber core is removed from the bottle, the drying mold is opened, and the product is removed from the mold (Fig. 18D).

Injection molding

Figure 19 shows an example of a device used for the production of FMPPs using the injection molding technique. The most important element of this device is the heated injection form having the shape of the manufactured product (similar to that shown in Fig. 8), placed in the form chamber (1). This form is equipped with a closing/opening mechanism, a heating system (which can heat the form up to a temperature of 150 °C to 180 °C), a steam removal system released during drying the production mixture, and a door that allows the finished product to be removed from the form chamber (2). The production material is so-called PIM granulate, which is a mixture of pulp (60 wt. %) and starch with the addition of PAV (40 wt.%), is supplied to the form through the special channel thanks to the action of the screw (3) placed in the central part of the device and the pressure of 170 to 260 atm produced by the mechanism placed on the right side of the device (4). The

production mixture enters the unit from a PIM conical storage container (5) located above the screw channel (3) (DAIHO 2025).

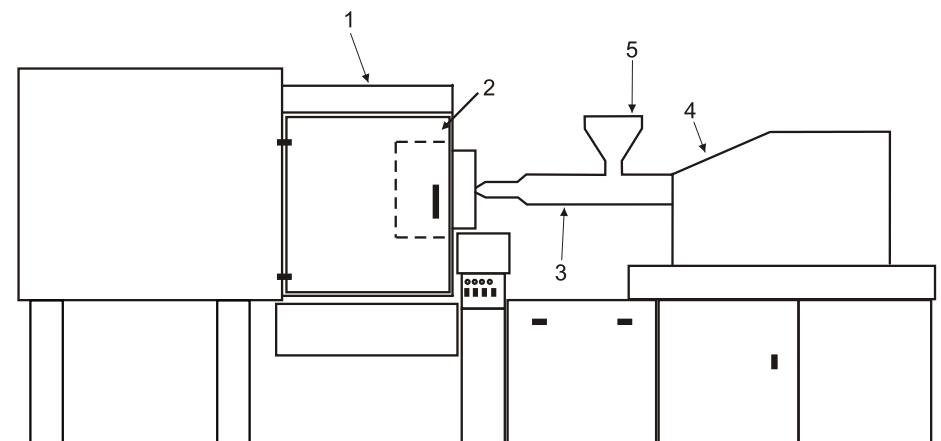


Fig. 19. Device for the manufacture of *injection molded* products

Tabular comparison of vacuum- and overpressure molding techniques

Due to the small amount of information regarding the comparison of vacuum molding, hydraulic molding, pressurized air molding, and injection molding methods, Table 1 presents such a comparison based on the information presented by Sterlingov (1963) and DAIHO (2025). This information indicates a fairly advanced development of the technique of manufacturing *thick-walled* and *transfer-pressed* FMPPs already in the years 1950-1960 (pre-plastic period), probably not manufacturing thermoformed products at that time, and that currently, in fact, in some cases (*pressurized air molding*), there has been a return to the production of products manufactured much earlier.

Table 1. Comparison of Different Techniques for Obtaining FMPPs in the Paper Industry

	Vacuum Molding	Overpressure Molding		
Variants of the method	- without pressing (<i>thick-walled</i>) - with additional pressing (<i>transfer-pressed</i>), including strong pressing (<i>strongly wet-pressed</i>) - with pressing during quick drying (<i>thermoformed</i>)	Hydraulic molding	Pressurized air molding	Injection molding
Principle of production	Continuous operation. Vacuum-forced deposition of fibers on the production mold surface.	Periodic operation. Fiber deposition on the surface of production mold forced by hydraulic pressure (pump, piston press).	Periodic operation. Fiber deposition on the surface of production mold forced by pressurized air.	Periodic operation. Pressure filling of free space in the production mold with e.g., PIM.
Type of product manufactured	- thick, smooth on one side - medium thickness, smooth on both sides,	- thick (wall thickness from 3 to 60 mm wet), larger sizes or	- products that are difficult to obtain using other techniques, e.g. vessels with lower	- high-quality products, difficult to obtain using other techniques, thin-walled, containing

	- thin, increased smoothness on both sides, higher density, - deep, high density, smooth on both sides.	requiring increased density	walls perpendicular to the side walls and tapering upper walls	microshapes, multi-rib structures, hinge shapes, and easy to print
Production equipment	- rotary, multimold type, only suction mold, - rotary, multimold type with suction molds and transfer molds, - sliding, multimold type with mold and thermomold, - with one press-mold.	- with replaceable, sliding, hermetically sealed production chambers.	- an automatic type device with pulp dosing system,	- automatic type, equipped with a system for injecting the production mixture into the thermoform.
Production forms	- one-piece or two-part, perforated, FMPP-shaped, covered with mesh	- two-part, sieve type, chamber type	- two-part, sieve type, automatically closed	- two-part, heated, automatically closed
Production material	- waste paper papermaking pulps, virgin papermaking pulps, or mixtures of these pulps			- a mixture of papermaking pulp, starch, and polyvinyl alcohol (so-called PIM material)
Examples of technological parameters of the forming device operation	Shopper-Riegler freeness of wood pulp: 35-50 °SR, for kraft pulp: 17-26 °SR, consistency of pulp suspension: approx. 1%, vacuum size: 100-500 mmHg, product thickness: up to 10 mm, regulated by the time of immersion of the mold in the pulp suspension, the vacuum size, and pulp consistency. Drying of the product in a drying chamber. In the case of products dried in a drying chamber on a conveyor or trolleys without placing them in molds, additional pressing (calibration) of the product moistened to 8-10% moisture is recommended. Thickness after forming: 22 mm, transfer-pressing: 11, drying: 7 mm, calibration: 4 mm.	Pulp slurry consistency: up to 2.5%, pulp slurry overpressure during forming: 6-12 atm, product thickness regulated by the fibrous suspension consistency, density in "cold" FMPPs: 0.3 g/cm ³ , using additional thermopressing: 0.65-1.0 g/cm ³ . Product drying as in the case of products manufactured by the vacuum FM method.	Number of workstations: 10, dimensions of the former: length: 7.5 m, width: 1 m, height: 3.8 m, weight: 4.2 t, power consumption: 1.5 kW/h, number of operating persons: 1, consistency of pulp suspension: in the pulp tank 0.7-1.5%, in the feeder before flowing into the matrices: 0.5-0.6%, hot air overpressure: 4.0 atm., hot air temperature: 370-400 °C, capacity of produced FMPPs: 0.25-5 dm ³ , wall thickness: 1.25 – 3 mm, time required to manufacture the product: 42-81 sec.	Mold thickness: 220-410 mm, mold dimensions: 325 × 325 mm, hopper capacity: 25 liter, screw diameter: 26-40 mm, injection capacity: 59-182 cm ³ , injection pressure: 176-265 MPa, injector rate: 159-255 cm ³ /s, heater band capacity: 7-10.5 kW, machine weight: 4.8-5 t.

CURRENT AND FUTURE TRENDS IN THE DEVELOPMENT OF FMPPs PRODUCTION

In recent years, a development opportunity has emerged for the paper industry consisting of the possibility of increasing its production through manufacturing increased amounts of the FMPPs for different use instead of such products made of synthetic polymers. This comes from the fact that FMPPs adhere to the circular economy's tenets,

which include minimizing the impact of waste disposal on the environment after its life cycle is complete, enhancing the reuse of waste as resources, and reducing waste through ongoing resource reuse. As a result, even though FMPPs often have lower surface and dimensional quality at first than items of similar use manufactured of synthetic polymers, customers and decision-makers have accepted them. On the other hand, these attributes have been improved after the start of production of these products using *thermoforming* and *injection-molding* methods. However, maintaining the increase of FMPPs production requires continuous improvement of the FMPPs manufacturing process in order to improve their quality and reduce production costs.

This requires (Singh *et al.* 2023):

- (1) Expanding knowledge on the effect of various types of fibrous papermaking pulps on the properties of FMPPs.
- (2) Determining the effect of alternative waste non-papermaking raw materials on the quality of these products and the possibility of use and cost of production.
- (3) Further understanding of the mechanisms of FM and drying of products obtained by this method.
- (4) Determining the effectiveness of already developed methods of improving the cushioning, strength, barrier, and utility properties of FMPPs in industrial conditions.
- (5) Implementing the latest solutions in the scope of FMPPs production devices into industrial practice.
- (6) Directing the organization of production of these products in order to increase its volume and reduce costs.
- (7) Striving to develop a technology of production of products which are very difficult to produce using FM method (like bottles, buckets, panels, suitcase bodies, *etc.*).
- (8) Improving the packaging properties of FMPPs using an intelligent component.

As already mentioned, some work has been carried out so far on the influence of several types of papermaking pulps on the properties of FMPPs (Corwin 1972; Ahn 1994; Gavazzo *et al.* 2003, 2005; Kirwan 2013; Aguerre and Garvazzo 2016; Zhao *et al.* 2020; Dislaire *et al.* 2021a; Wang *et al.* 2021; Wang *et al.* 2019; Debnath *et al.* 2022; Liu *et al.* 2023). However, the number of types of these pulps is much larger. The following types can be distinguished: made of wood, made of non-wood raw material, made of waste paper (undeinked, deinked), obtained using chemical (kraft, soda, sulfite) methods, semi-mechanical methods (NSSC, Cold-Soda, kraft, sulfite), mechanical (SGW, PGW, S-PGW, TMP, CTMP, BCTMP, APMP) methods, long-fibered (softwood, many different species), short-fibered (hardwood, many different species), and pulp blends. Particularly valuable and useful for industrial practice would be works comparing the effect of several types of pulps on the properties of FMPPs within a specific group of them and determining the boundary ranges of these properties.

Another important issue, from the point of view of reducing the costs of producing FMPPs that requires expanding knowledge, is the already initiated topic regarding the effects that could be achieved as a result of using alternative waste raw materials for the production of these products in relation to the often expensive fibrous paper pulps, such as residuals from agriculture and the food industry, including, for example, coconut husk, orange and fruit pomace, spent grain, pineapple leaves, and banana stems, pith mixture of fruits peels, waste oil palm empty fruit bunch fibers (Anon. 2011; Gouw *et al.* 2017; Buxoo and Jeetah 2020; Rattanawongkun *et al.* 2020; Liu *et al.* 2021). This also applies to the so-called bulk additives such as curcumin, anthocyanins, chlorophyll, tannins and carotenoids,

amaranthus leaf extract, and many others, demonstrating the ability to give FMPPs an active character towards specific factors affecting the packaging itself and the product contained therein without negatively affecting their harmfulness and biodegradability (Chavoshizadeh *et al.* 2020; Kanatt 2020; Singh *et al.* 2020).

The mechanisms of various FM processes and their drying processes can be considered as requiring further research. The publications of Didone and Tosello (2018) can be cited as an example of this type of work. They dealt with the basic characterization of the *thermoforming* process in terms of the dewatering efficiency of the process, a quantification of the molding geometrical accuracy, and an analysis of the internal microstructure of the parts. In these studies it was established that the dewatering efficiency is mainly governed by the mold's temperature, while the duration of the contact time is not influential. Geometrical accuracy of the moldability appeared to be dependently related to the pulp type employed, while internal microstructure showed an increase in the internal void fraction linked with an increase in the mould's temperature. The topic of the second work by the same authors (Didone and Tosello 2018) was understanding and controlling the impulse drying phenomena. It was found that in this drying technique, the moving vapor layer can assist the dewatering process by displacing the bound water and that this process can be considered in terms of two main process steps: heat conduction and vapor-water diffusion and the packaging industry would benefit from impulse drying application because it would reduce energy consumption. Later it was also established that in the case of drying FMPPs obtained using the *thermoforming* process it is justified to investigate the drying in this process, distinguishing between the water removal due to only compression (better known as cold pressing) and the water removal under additional thermal conditions.

In view of the quite significant number of different possibilities of improving the cushioning, strength, barrier, and functional properties of FMPPs presented in this article, as well as the existence of other solutions regarding this issue (Didone *et al.* 2017; Su *et al.* 2018; Zhang *et al.* 2021; Sengupta *et al.* 2020; Dey *et al.* 2020; Debnath *et al.* 2022; Semple *et al.* 2022), it seems advisable to present the practical and cost-effectiveness of these already developed methods of improving these properties based on tests under industrial conditions and present the results.

An important trend in the production of FMPPs in the future should certainly be the implementation of the latest solutions regarding production devices, enabling the increase in production and reduction of its costs (energy, water). The greatest progress in this area is possible to achieve mainly in companies producing production devices for FMPPs plants. Below are some current trends in the development of FMPPs production equipment in these companies (EAMC 2025; Xuy 2025).

- The development of high-speed machines that can produce large volumes of products in a short time.
- Design of fully automatic pulp FM machines, with trimming and side punching equipment completed in one machine.
- Offering of equipment for molding of special FMPPs (*e.g.* cup lids) and high-quality products (fine molded products).
- Equipping production facilities for possibility of manufacturing several types of FMPPs in one device, *e.g.*, tableware, hot drink cup lids with inverted buckles, premium small-angle industrial packaging, boutique egg boxes, egg trays, fruit and vegetable trays, etc.

- Compact design of production devices characterizing production capacity 2-3× the output of a conventional machine at the same machine size (it greatly reduces civil construction costs, plant rents, and management costs).
- Fully enclosed construction of the machines produced for safety protection (automatic stop when the door is opened during operation).
- High productivity (fast cycle) devices, characterized by low energy consumption (*e.g.*, about 30% lower than the conventional equipment), lower labor cost, and floor space needed to install.
- High degree of automation of FM machines, using PLC engineering and intelligent touch screen control system, simple operation and precise control of the forming process and drying (*e.g.*, temperature, fan, dehumidification, and drive speed). Intuitive working status of the equipment with fault display and alarm functions.
- Possibility of use of greater fiber types in practical use of the device.
- Implementing design solutions enabling obtaining a high-quality smooth surface for full-color printed graphics on both sides, dimensional accuracy of the product, low product draft angles, and greater depth of the form, creating new product designs not previously possible with rotary machines.

An example of application these guidelines in industrial practice can be the machine of EAMC company (Fig. 20).



Fig. 20. Drawing of fully automatic pulp molding machine of EAMC company for production of tableware using *thermoforming* method (EAMC 2025).

Another important issue for companies involved in the production of FMPPs that may have a significant impact on the development of FMPPs production is their development of strategy in terms of sizing and scheduling of this production. This involves decisions about setting up appropriately the production process to meet the demands of different products in the molding stage, where the mix of products manufactured simultaneously depends on the combination of molds attached to the molding machine,

called the molding pattern. Thus, the problem lies in deciding which molding patterns should be used, how long each pattern should be used, and the production sequence that they should be scheduled. Martínez *et al.* (2016) propose a novel optimization approach to deal with this problem by considering some possible settings for the molding machine based on specific technological constraints. These preset settings are included in a mixed integer programming model to define the molding patterns and to deal with the production lot sizing and scheduling decisions. Since the molding patterns are defined by the approach, three types of production setup times and costs (some of them are sequence-dependent) must also be calculated and taken into account in the planning decisions. Computational tests with real data from a Brazilian molded pulp plant showed that the production plans generated by this approach are suitable in practical settings, as well as define molding patterns different from those commonly used and simultaneously reduce setup times and costs when compared to the production plans of the company.

There are FMPPs products in the case of which the production seems to be very difficult (bottles and jars) using FM technique. In this case, the problem is both the production of the body of such products and obtaining a complete barrier on the inner side of these products for a longer period of time for liquid products transported in them and chemical inertness towards these products, which is easily obtained in the case of their production from plastic or glass.

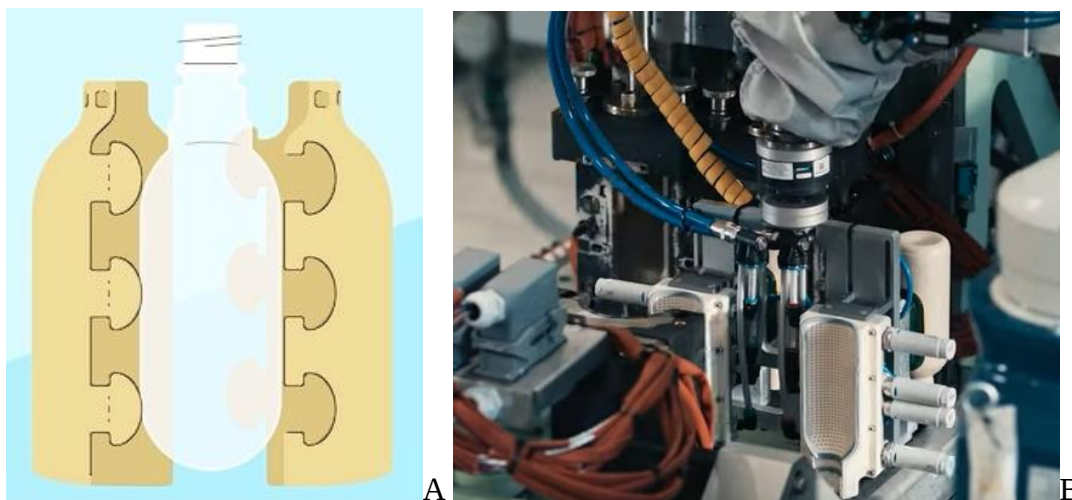


Fig. 21. Ecologic bottle design, *i.e.* foldable outer paper shell and inner thin plastic liner and spout (EAMC 2025) and a machine for making Paboko type paper bottles using the pressurized air molding method (YT-2 2025).

A well-known solution to this problem is the production of containers consisting of a foldable outer body, made of fibrous pulp produced by the FM method, the production of foil, thin, recyclable inner pouch from synthetic polymers and connection these parts together (Cousins 2014; Ahuja *et al.* 2024). In this case, however, the packaging is produced only with a reduced share of plastic, and therefore is not completely biodegradable or biocompostable, although the materials used to provide barrier properties may be biobased. In this case, the paper outer shell is made of two halves joined together using special interlocking tabs (Fig. 21A), as, for example, in the case of Eco.Bottle of Ecologic Brand Company (Cousins 2014; EC 2025) and Frugal Bottle of Frugalpac. A more advanced method of producing bottles from fibrous pulp has been implemented in the case of the Paboco bottle from The Paper Bottle Company (YT – 2 2025; Carlsberg

2025) (Fig. 21b), which is produced entirely by the pressurized air molding method (YT – 2 2025). This indicates a return to the previously known method of manufacturing paper containers (Fig. 17).

According to Ahuja *et al.* (2022), bottles made entirely of fiber pulp are also manufactured by Kagzi Company (India). The internal barrier of these bottles is obtained by the spray coating method. In this method, a pressure-assisted nozzle is used to spray the coating substance, dissolvable in highly volatile solvents, on the paper inner wall of the container from a distance which is in rotation motion. Other methods of applying a layer of the barrier substance may be the rotacasting coating and blow molding of the inner liner methods (Ahuja *et al.* 2022).

When reviewing the references, only a few pieces of information were found concerning the practical application of the *strongly wet-pressed molding* and *hydraulic molding*. Sterlingov (1961) wrote more extensively about these techniques. From his account, it is clear that this was a technique used to produce deep FMPPs, such as, *e.g.*, buckets and bowls, requiring increased wall density of wet pulp semi-product, which was important from the point of view of their further processing, as well as the properties of the finished product. Since such plastic products also contribute significantly to environmental pollution, it may be worth considering the possibility of returning to the known technology of their production from pulp using these methods.

As for the possibility of production of FMPPs with intelligent components, it is speculated that they could enable the control of the permeability of gaseous substances through their walls in order to extend the shelf life of food, delay its degradation (moisture content, fat oxidation, development of microorganisms), control storage time, temperature, and shelf life by adding indicator elements to FMPPs (Janjarasskul and Suppakul 2018; Firouz *et al.* 2021).

SUMMARY

The production of paper products using the FM method has a long tradition in the papermaking industry. Interest in the production of these types of products is growing again after a period of stagnation in their production in the 70s and 80s of the previous century.

There are two basic variants of this method in which the effect of molding of fibers on the sieve mold is obtained. The first one is *vacuum molding*, and the second one is *overpressure molding*. Using the first technique, such FMPPs can be obtained like the one-sided smoothed (*thick-walled*), two-sided smoothed (*transfer-pressed*, *strongly wet-pressed*), and double-sided smooth (*thermoformed*). The second method is used for the production of such FMPPs having thickness of walls greater than 3 mm (*hydraulic molding*), complex-shaped products (*e.g.*, containers) (*pressurized air molding*), and those with very good quality edges, super smoothness, complex-shaped, and containing microshapes (*injection-molded* products). The last group of FMPPs includes *processed* products, which include any type of FMPPs that was additionally refined after the drying process.

This work also addressed the state of knowledge on the FM techniques used in the past to produce FMPPs. It presents construction of devices probably not published in review articles for producing FMPPs using *strongly wet-pressed molding*, *hydraulic molding*, and *pressurized air molding* methods and compares *vacuum* and *overpressure molding* methods in a descriptive and summary forms. It can now be stated that the

pressurized air molding technique has been recreated in the production of bottles. Perhaps the *strongly wet-pressed molding* and *hydraulic molding* technique will also be reactivated for the production of hard molded articles, which would be a classic example of history coming full circle.

An important issue in the case of FMPPs from the point of view of expanding the scope of their application to food packaging and products manufactured using *strongly wet-pressed molding*, *hydraulic molding* and *pressurized air molding* techniques is the availability of methods for giving them higher strength and barrier properties and methods for finishing their external and internal surfaces. The review showed papermaking industry had the methods obtain such effects. However, now, more ecological methods are needed and the state of knowledge in this scope has expanded, lately, and tie has come to determine the usefulness of many developed methods in industrial and utility conditions.

The article also attempted to determine the directions of development of FMPPs manufacturing technologies and techniques in the future with a broader discussion of some of them. These data indicate that the production of FMPPs is encompassing an increasing number of different issues and is becoming an increasingly specialized field of papermaking similarly like paperboard making has become many years ago.

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REFERENCES CITED

- Ahn, B. K. (1994). "Studies on the characteristics of molded pulp trays [used] as a packaging material," *J. Tech. Assoc. Pulp Paper Ind. Korea* 26(4), 33-40.
- Ahuja, A., Samyn, P. and Rastogi, V.K. (2022). "Paper bottle: Potential to replace conventional packaging for liquid," *Biomass Conversion and Biorefinery* 14(13), 13779-13805. DOI: 10.1007/s13399-022-03642-3.
- Amono, K., Omoniyi, T. M., and Onilude, M. A. (2022). "Development and performance evaluation of a low-cost paper egg tray making machine," *Scientific African* 16, article e01176. DOI: 10.1016/j.sciaf.2022.e01176
- Andrady, A. L. (2011). "Microplastics in the marine environment," *Marine Pollution Bulletin* 62, 1596-1605. DOI: 10.1016/j.marpolbul.2011.05.030Get rights and content
- Anon. (1967). "Final program for deinking conference," *TAPPI J.* 50(8), 143A-144A.
- Anon. (2011). "Moulded pulp products – Overview and developments," *Paper Technology* 52(6), 28-29.
- Aquerre, Y. S., and Gavazzo, G. B. (2016). "Lignocellulosic recycled materials to design molded products: Optimization of physical and mechanical properties," *Journal of Materials Science and Engineering A* 6(4), 222-231. DOI: 10.1765/2161-6213/2016.7-8.005.
- AVP LCC (2018) <http://www.avpllc.info/featured-products/egg-traymoulding-lines/zmz-2296-pulp-moulding-machine-for-8000-egg-trayshour>
- Back, E. L., and Salmen, N. L. (1982). "Glass transitions of wood components hold implications for molding and pulping processes," *TAPPI J.* 65(7), 107-110.

- Balea, A., Merayo, N., Fuente, E., Negro, C., and Delgado-Aguilar, M. (2018). "Cellulose nanofibers from residues to improve linting and mechanical properties of recycled paper," *Cellulose* 25(2), 1339-1351. DOI: 10.1007/s10570-017-1618-x.
- Barnes, D. K. A., Galgani, F., Thompson, R. C., and Barlaz, M. (2009). "Accumulation and fragmentation of plastic debris in global environments," *Philosophical Transactions of the Royal Society B: Biological Sciences* 364, 1985-1998. DOI: 10.1098.
- BeSure Technology Co., Ltd. (2025). <https://www.youtube.com/watch?v=Uat7S7zY9AA>
- Briard, M., Brien, S. O., and Pelsy, F. (2018). "A European strategy for plastics in the circular economy. Local and regional dimension," European Union, Commission for the Environment, Climate Change and Energy. DOI: 10.2863/734820.
- Buxoo, S., and Jeetah, P. (2020). "Feasibility of producing biodegradable disposable paper cup from pineapple peels, orange peels and Mauritian hemp leaves with beeswax coating," *SN Applied Science* 8(2), 1-15. DOI: 10.1007/s42452-020-3164-7.
- Carlsberg (2025). <https://www.carlsberg.com/en/green-fibre-bottle/>
- Carlson, R. L. and Horowitz, F. (1960). "Upgrading of molded pulp products through the use of synthetic resins," *TAPPI J.* 43(2), 185A-188A.
- Casey, J. F. (1961). *Pulp and Paper. Chemistry and Chemical Technology*, Second Edition. Interscience Publishers Press, Inc. New York.
- Cazón, P., Velazquez, G., Ramírez, J. A., and Vázquez, M. (2017). "Polysaccharide-based films and coatings for food packaging: A review," *Food Hydrocolloids* 68, 136-148. DOI: 10.1016/j.foodhyd.2016.09.009.
- Chavoshizadeh, S., Pirsá, S., and Mohtarami, F. (2020). "Sesame oil oxidation control by active and smart packaging system using wheat gluten/chlorophyll film to increase shelf life and detecting expiration date," *European Journal of Lipid Science and Technology* 122(3), article 1900385. DOI: 10.1002/ejlt.201900385.
- Chen, F.-S., Quin, Z., Xu, Z., Wu, L., Wei, Y., Wang, X., and Duns, G. J. (2012). "Utilization of an invasive species (*Spartina alternifolia*) in the molded pulp industry," in: 23th Asian-Pacific Weed Science Society Conference 18, 137-146.
- Corwin, H. E. (1972). "Limitation in using secondary fibre (in molded pulp articles)," *TAPPI J.* 55(5), 787.
- Cousins, S. (2014). "Bottled up," *Pulp Paper International* 46(5), 25-27.
- Curling, S. F., Laflin, N., Davies, G. M., Ormondroyd, G. A., and Elias, R. M. (2017). "Feasibility of using straw in a strong, thin, pulp moulded packaging material," *Industrial Crops and Products* 97, 395-400. DOI: 10.1016/j.indcrop.2016.12.042.
- DAIHO Industrial Co., Ltd (2025). http://www.daiho.com/image/pim/PIM_English.pdf.
- Das, P., Gabriel, J. C. P., Tay, C. Y., and Lee, J. M. (2021). "Value-added products from thermochemical treatments of contaminated e-waste plastics," *Chemosphere* 269, article 129409. DOI: 10.1016/j.chemosphere.2020.129409.
- Debnath, M., Sarder, R., Pal, L., and Hubbe, M. A. (2022). "Molded pulp products for sustainable packaging: Production rate challenges and product opportunities," *BioResources* 17(2), 3810-3870. DOI: 10.15376/biores.17.2.Debnath
- Dey, A., Sengupta, P., Pramanik, N. K., and Alam, T. (2020). "Paper and other based eco-friendly moulded materials for food packaging applications: A review," *Journal of Postharvest Technology* 8(3), 1-21.
- Didone, M. (2020). "Molded pulp products manufacturing: process development, characterization and modeling," Ph. D. thesis, Technical University of Denmark.
- Didone, M., Saxena, P., Brillhuis-Meijer, E., Tosello, G., Bissacco, G., Mcaloone, T. C.,

- Pigasso, D. C. A., and Howard, T. J. (2017). "Moulded pulp manufacturing: Overview and prospects for the process technology," *Packaging Technology and Science* 30, 231-249. DOI:10.1002/pts.2289
- Didone, M., and Tosello, G. (2016). "Potential for impulse drying technology for moulded pulp product manufacture," *Proceedings of Progress in Paper Physics Seminar* 1 September, Darmstadt, Germany.
- Didone, M., and Tosello, G. (2019). "Moulded pulp products manufacturing with thermoforming," *Packaging Technology and Science* 32(1), 7-22. DOI: 10.1002/pts.2412.
- Didone, M., Mohanty, S., Hattel, J. H., Sonne, M. R., Fiordaliso, E. M., Checchi, A., and Tosello, G. (2020). "On the drying process of molded pulp products: Experiments and numerical modelling," *Drying Technology* 38(12), 1644–1662. DOI:10.1080/07373937.2019.1653905.
- Drzewińska, E. (2010). "Packaging from paper pulp," *Opakowanie* 7, 14-15 (in Polish).
- Dislaire, C., Grohens, Y., Seantier, B., and Muzy, M. (2021a). "The impact of molded pulp product process on the mechanical properties of molded bleached chemi-thermo mechanical pulp," *Functional Composite Materials* 2(7), 1-10. DOI: 10.1186/s42252-021-00023-3.
- Dislaire, C., Seantier, B., Muzy, M., and Grohens, Y. (2021b). "Mechanical and hygroscopic properties of molded pulp products using different wood-based cellulose fibers," *Polymers* 13(19), article 3225. DOI: 10.3390/polym13193225.
- Eagleton, D. G., and Marcondes, J. A. (1994). "Cushioning properties of moulded pulp," *Packaging Technology and Science* 7(2), 65-72. DOI: 10.1002/pts.2770070203.
- EAMC (2025). https://www.fibermolding.com/pulp-molding-machine.html?gad_source=1&gclid=EAIaIQobChMI1Y-s5KfBjAMVoyCiAx3oOQ4ZEAAYASAAEgK_e_D_BwE
- EC (2025). "Packaging the earth can live with," <https://www.ecologicbrands.com/>
- Emery, R. W., and Emery, J. R. (1966). "Review of pulp molding industry and processes used," *Paper Trade J.* No. 1, 29-33.
- Firouz, M. S., K. Mohi-Alden, and Omid, M. (2021). "A critical review on intelligent and active packaging in the food industry: research and development," *Food Research International* 141, article 110113. DOI: 10.1016/j.foodres.2021.110113.
- FMI. (202). <https://www.futuremarketinsights.com/reports/pulp-moulding-machines-market>. (Accessed on 1.04.2025).
- Gällstedt, M., and Hedenqvist, M. S. (2006). "Packaging-related mechanical and barrier properties of pulp-fiber-chitosan sheets," *Carbohydrate Polymers* 63(1), 46-53. DOI: 10.1016/j.carbpol.2005.07.024.
- Garcia, J. M., and Robertson, M. L. (2017). "The future of plastics recycling," *Science* 358, 870-872. DOI: 10.1126/science.aag0324.
- Gavazzo, G. B. Lanouette, R., and Valade, J. L. (2003). "Study of the important variable of a pulp molding process," *ATIP. Association Technioque de L'Industrie Papeterie* 57(4), 47-52, 54-55.
- Gavazzo, G. G., Lanouette, R., and Valada, J. L. (2008). "Production of molded pulp at laboratory scale," *Progress in Paper Recycling* 14(2), 20-25.
- Geyer, R., Jambeck, J. R., and Law, K. L. (2017). "Production, use, and fate of all plastics ever made," *Science Advances* 3(7), 25-29. DOI: 10.1126/sciadv.1700782.
- Głuchowski, K. (1969). "Production of trays embossed from paper pulp for food products," *Przegląd Papierniczy* 25(11), 372-376 (in Polish).

- Government of Canada. (2020). "Toward zero plastic waste," <https://www.canada.ca/en/environment-climate-change/services/managing-reducing-waste/zero-plastic-waste.html> (accessed 04.01.21).
- Gouw, V. P., Jung, J., Simonsen, J., and Zhao, Y. (2017). "Fruit pomace as a source of alternative fibers and cellulose nanofiber as reinforcement agent to create molded pulp packaging boards," *Composites. Part A Applied Science and Manufacturing* 99, 48-57. DOI: 10.1016/j.compositesa.2017.04.007.
- Gurav, S. P., Bereznitski, A., Heidweiller, A., and Kandachar, P. V. (2003). "Mechanical properties of paper-pulp packaging," *Composites Science and Technology* 63(9), 1325-1334. DOI: 10.1016/S0266-3538(03)00104-0.
- Haber, Z. (1989). "Peat pots," *Przegląd Papierniczy* 45(12), 403-407 (in Polish).
- Hamzeh, Y., Ashori, A., Khorasani, Z., Abdulkhani, A., and Abyaz, A. (2013). "Pre-extraction of hemicelluloses from bagasse fibers: Effects of dry-strength additives on paper properties," *Industrial Crops and Products* 43(1), 365-371. DOI: 10.1016/j.indcrop.2012.07.047.
- Han, J. H., and Krochta, J. M. (2001). "Physical properties and oil absorption of whey protein-coated paper," *Journal of Food Science* 66(2), 294-299. DOI: 10.1111/j.1365-2621.2001.tb11335.x.
- Han, G. (2022). "Characterization and properties of nanocellulose-enhanced pulp-molded lunch boxes," *Journal of Physics Conference Series* 2393, article 012006. DOI: 10.1088/1742-6596/2392/1/01/2006.
- Hassan, E. A., Hassan, M. L., Abou-Zeid, R. E., and El-Wakil, N. A. (2016)., "Novel nanofibrillated cellulose chitosan nanoparticles nanocomposites films and their use for paper coating," *Industrial Crops and Products* 93, 219-226. DOI: 10.1016/j.indcrop.2015.12.006
- Hoffmann, J. (2000). "Compression and cushioning characteristics of moulded pulp packaging," *Packaging Technology and Science* 13(5), 211-220. DOI: 10.1002/1099-1522(200009)13:5<211::AID-PTS515>3.0.CO;2-0.
- Horejs, C. (2020). "Solutions to plastic pollution," *Nature Reviews Materials* 5, article 641. DOI: 10.1038/s41578-020-00237-0.
- Hann, S., Etlinger, S., Gibbs, A., Hogg, D., and Ledingham, B. (2017). "Study to provide Information supplementing the study on the impact of the use of 'oxo-degradable' plastic on the environment," Final Report for the European Commission DG Environment. DOI: 10.2779/081633.
- Huang, L., He, K., and Wang, D. (2009). "Research on the processing technique, common problems and measures of molded pulp products," *Packaging and Food Machinery* 27(3), 51-54.
- Hubbe, M. A. (2006). "Paper's resistance to wetting – A review of internal sizing chemicals and their effects," *BioResources* 2(1), 106-145. DOI: 10.15376/biores.2.1.106-145.
- Hubbe, M., and Gill, R. (2016). "Fillers for papermaking: A review of their properties, usage practices, and their mechanistic role," *BioResources* 11(1), 2886-2963. DOI: 10.15376/biores.11.1.2886-2963.
- Jambeck, J. R., Geyer, R., Wilcox, C., Siegler, T. R., Perryman, M., Andrady, A., Narayan, R., and Law, K. L. (2015). "Plastic waste inputs from land into the ocean," *Science* 347(6223), 768-771. DOI: 10.1126/science.1260352.

- Janjarasskul, T., and Suppakul, P. (2018). "Active and intelligent packaging: The indication of quality and safety," *Critical Reviews in Food Science and Nutrition* 58 (5), 808-831. DOI: 10.1080/10408398.2016.1225278.
- Ji, H., and Wang, H. (2011). "Short span compressive stress-strain relation and model of molded pulp material," *Key Engineering Materials* 450, 202-205. DOI: 10.4028/www.scientific.net/KEM.450.202.
- Kalajo, T. E., Onilude, M. A., Omoniyi, T.E., and Oladosu, O. T. (2021). "The design and construction of a pulp molding machine," *International Journal of Engineering Research & Technology* 10(6), 798-802.
- Kanatt, S. R. (2020). "Development of active/intelligent food packaging film containing Amaranthus leaf extract for shelf life extension of chicken/fish during chilled storage," *Food Packaging and Shelf Life* 24, article 100506. DOI: 10.1016/j.fpsl.2020.100506
- Keyes, F. E. (1890). "Method of molding pulp articles," U.S. Patent 424003A, 25 March 1890. 30.
- Keyes, M. L. (1903). "Apparatus for making pulp articles," U.S. Patent 740023A, 29 September 1903.
- Kisonen, V., Prakobna, K., Xu, C., Salminen, A., Mikkonen, K. S. Valtakari, D. Eklund, P., Seppälä, J., Tenkanen, M., and Willför, S. (2015). "Composite films of nanofibrillated cellulose and O-acetyl galactoglucomannan (GGM) coated with succinic esters of GGM showing potential as barrier material in food packaging," *Journal of Material Science* 50(8), 3189-3199. DOI: 10.1007/s10853-015-8882-7.
- Kirwan, M. J. (2013). "Paperboard-based liquid packaging," in: *Handbook of Paper and Paperboard Packaging Technology*, 2nd Ed.. Wiley. DOI: 10.1002/9781118470930.
- Kucherer, H. (1995). "Blow-molded containers made of paper," *Der Papiermacher* 45(7), 106-107.
- Kumamoto, Y., Otakura, S. Otani, K., Odajima, S., and Tsuura, T. (2002). "Method of manufacturing pulp molded products," US Patent 6,468,398 B1.
- Kumamoto, Y., and Otani, K. (2001). "Method for producing pulp molded article," US 2001/0040016 A1.
- Leman, G. (1968). "Fundamentals of technology production of paper and cartonboards," Lesnaya Promyslennost Press, Moskva (in Russian).
- Li, W., Wang, S., Wang, W., Qin, C., and Wu, M. (2019). "Facile preparation of reactive hydrophobic cellulose nanofibril film for reducing water vapor permeability (WVP) in packaging applications," *Cellulose* 26, 3271-3284. DOI:10.1007/s10570-019-02270-x.
- Liu, C., Luan, P., Li, Q., Cheng, Z., Sun, X., Cao, D., and Zhu, H. (2020). "Biodegradable, hygienic, and compostable tableware from hybrid sugarcane and bamboo fibers as plastic alternative," *Matter* 3(6), 2066-2079. DOI: 10.1016/j.matt.2020.10.004.
- Liu, Y., Ma, S., Wang, F., and Wang, L. (2023). "Advances in research of molded pulp for food packaging," *Journal of Renewable Materials* 11(11), 3831-3846. DOI: 10.32604/jrm.2023.028251.
- Liu, Q. Y., Loxton, C., Mohamed, A. A., Jawaid, M., Braganca, R. et al. (2021). "Development of pulp moulded packaging samples from empty fruit bunch fibre," *Pertanika Journal of Science and Technology* 29(4), 2901-2912. DOI: 10.47836/pjst.29.4.36.

- Ma, X., Sah, A. K., and Wang, B. (2004). "A design database for moulded pulp packaging structure," *Packaging Technology and Science* 17, 193-204. DOI: 10.1002/pts.658.
- MacLeod, M., Arp, H. P. H., Tekman, M. B., and Jahnke, A. (2021). "The global threat from plastic pollution," *Science* 373, 61-65. DOI: 10.1126/science.abg5433.
- Martínez, K. Y. P., Toso, E. A. V. and Morabito, R. (2016). "Production planning in the molded pulp packaging industry," *Computers & Industrial Engineering* 98, 554-566. DOI: 10.1016/j.cie.2016.05.024.
- Muniyasamy, S., Anstey, A., Reddy, M., Misra, M., and Mohanty, A. (2013). "Biodegradability and compostability of lignocellulosic based composite materials," *Journal of Renewable Materials* 1, 253-272. DOI: 10.7569/JRM.2013.634117.
- Nair, S. S., Trafiałek, J., and Kolanowski, W. (2023). "Edible packaging: A technological update for sustainable future of the food industry," *Applied Sciences* 13, article 8234 (1-23). DOI: 10.3390/app13148234.
- Noguchi, T., Miyashita, M., Seto, J., Tari, M., and Kawano, M. (1997). "Development of moulded pulp materials for the packaging of electronic equipment," *Packaging Technology and Science* 10, 161-168.
- Oliaei, E., Lindström, T., and Berglund, L. A. (2021a). "Sustainable development of hot-pressed all-lignocellulose composites—comparing wood fibers and nanofibers," *Polymers* 13, article 2747. DOI: 10.3390/polym13162747.
- Oliaei, E., Berthold, F., Berglund, L.A., and Lindström, T. (2021b). "Eco-friendly high-strength composites based on hot-pressed lignocellulose microfibrils or fibers," *ACS Sustainable Chemistry and Engineering* 9, 1899-1910.
- Onilude, M. A., Omoniyi, T. E., Akinyemi, B. A., and Adigu, K. A. (2013). "The design and fabrication of a recycled paper egg tray machine," *American International Journal of Contemporary Management* 3(3), 142-151.
- Paavilainen, L. (2000). "Quality-competitiveness of Asian short-fibre raw materials in different paper grades," *Paperi ja Puu* 82(3), 156-161.
- Palenik, K. (1954). "Production of pressed vessels from pulp," *Przegląd Papierniczy* 10(10), 292-298 (in Polish).
- Park, H. J., Kim, S. H., Lim, S. T., Shin, D. H., Choi, S., and Hwang, K. T. (2000). "Grease resistance and mechanical properties of isolated soy protein-coated paper," *Journal of the American Oil Chemists' Society* 77(3), 269-273. DOI: 10.1007/s11746-000-0044-2.
- Pasquier, E., Mörseburg, K., Syverud, K. and Ruwoldt, J. (2024). "Effect of raw material and process conditions during the dry forming of CTMP fibers for molded pulp products," *Journal of Natural Fibers* 21(1), article 2409890. DOI: 10.1080/15440478.2024.2409890.
- Pasquier, E., Skunde, R., and Ruwoldt, J. (2023). "Influence of temperature and pressure during thermoforming of softwood pulp," *Journal of Bioresources and Bioproducts* 8, 408-420. DOI: 10.1016/j.jobab.2023.10.001.
- Pelton, R. (1989). "Review of brown stock defoamer fundamentals," *Pulp and Paper Canada* 90(2), 61-68.
- Peng, Y., Zhang, J., Li, W., and Yue, J. (2007). "Study on oil repellent capability of molding dining boxes made from extruder chemi-mechanical bamboo pulp," *Forest Engineering* 23(02), 74-76.
- Pavlatková, L., Sedlářková, J., Pleva, P., Peer, P., Uysal-Unalan, I., and Janalíková, M. (2023). "Bioactive zein/chitosan systems loaded with essential oils for food-

- packaging applications,” *Journal of Science Food in Agriculture* 103, 1097-1104. DOI: 10.1002/jsfa.11978.
- Potashiev, A. B., Guriev, A. B., Filipov, I. B., and Mociejew, W. G. (2019). “Features of deformation of the structure of molded products from cellulose fibres,” *Liesnoj Journal* 2, 119-121. DOI: 10.17238/issn0536-1036.2019.2.119.
- Prasertpong, R., Rattanawongkun, P., Tawichai, N., Intatha, U., and Soykeabkaew, N. (2021). “Effect of valey beater refining on tensile properties of molded pulps from rice straw,” *Key Engineering Materials* 889(KEM), 73-78. DOI: 10.4028/www.scientific.net/KEMI.889.73
- Pulp-tec (2025). <https://www.pulp-tec.com/en/moulded-pulp>.
- QF. (2025). “ASTM D1596 Foam Test Methods,” <http://www.qualityfoam.com/ethafoam-spec-astm-d1596.asp>
- Quin, C., Li, J., Wang W., and Li, W. (2022). “Improving mechanical strength and water barrier properties of pulp molded product by wet-end added polyamide epichlorohydrin/cationic starch,” *ASC Omega* 7, 22173-22180. DOI: 10.1021/acsomega.1c07369.
- QSheng (2018). <https://www.pulpbiz.com/egg-tray-making-process> (Accessed on 2018).
- Rabbi, M. S., islam, T., and Sadicul Islam, G. M. (2021). “Injection-molded natural fiber-reinforced polymer composites a review,” *International Journal of Mechanical and Materials Engineering* 16(15), 1-21. DOI: 10.1186/s40712-021-00139-1.
- Rattanawongkun, P., Kunfong, N., Klayya, S., Chotimarnon, T., Duangphet, S. (2020). “Comparison of molded pulps from rice straw, pineapple leaf and banana stem pulps,” *ScienceAsia* 46, 79-84. DOI: 10.2306/scienceasia1513-1874.2020.S011.
- Rice, M. C., Pal, L., Gonzales, R., and Hubbe, M. (2018). “Wet-end addition of nanofibrillated cellulose pretreated with cationic starch to achieve paper strength with less refining and higher bulk,” *TAPPI J.* 17(7), 395-403. DOI: 10.32964/TJ17.07.395.
- Rijal, M. S., Nasir, M., Purwasasmita, B. S., Asri, L.A.T.W. (2023). “Cellulose nanocrystals-microfibrils biocomposite with improved membrane performance,” *Carbohydrate Polymer Technologies and Applications* 5, article 100326, DOI.org/10.1016/j.carpta.2023.100326.
- Ruwoldt, J., and Tanase Opedal, M. (2022). “Green materials from added-lignin thermoformed pulps,” *Industrial Crops and Products* 185 (1 October), article 115102. DOI: 10.1016/j.indcrop.2022.115102.
- Sandak, A., Jaszczur, A., Sandak, J., Modzelewska, I. (2015). “Near infrared assessment of biodegradability and mechanical properties of paper made of cellulose sulfate bleached coniferous pulp with addition of cationic starch and resinous adhesive,” *International Biodeterioration & Biodegradation* 97, 31-39. DOI: 10.1016/j.ibiod.2014.09.019.
- Saxena, P., and Bissacco, G. (2016). “Moulding process characterization of paper bottles using computed tomography,” PAN Pacific Conference. Current Research and Perspectives on Pulp, Paper and Lignocellulosic Materials. October 25-28, 2016, Seoul, Korea.
- Saxena, P., Bissacco, G., Gundlach, C., Dahl, V. A., Himmelstrup-Tridenerup, C., and Dahl, A. B. (2019). “Process characterization for molding of paper bottles using computed tomography and structure tensor analysis,” *9th Conference on Industrial Computed Tomography*, Padova, Italy.

- Saxena, P. Bissacco, G., Meiners, K. Æ., and Bedka, F. J. (2020). "Mold design and fabrication for production of thermoformed paper-based packaging products," *Journal of Manufacturing Process* 58, 311-321. DOI:10.1016/j.jmapro.2020.07.029.
- Semple, K. E., Zhou, C., Rojas, O. J., Nkeuwa, W. N., and Dai, C. (2022). "Moulded pulp fibres for disposable food packaging: A state-of-art review," *Food Packaging and Shelf Life* 33, article 100908. DOI: 10.1016/j.fpsl.2022.100908.
- Sengupta, P., Dey, A., Alam, T., and Pramanik, N. K. (2020). "Paper and other pulp based eco-friendly moulded materials for food packaging applications: A review," *J. Postharvest Technology* 8, 1-21.
- Sheng, J., Li, J. and Zhao, L. (2019). "Fabrication of grease resistant paper with non-fluorinated chemicals for food packaging," *Cellulose* 26(11), 6291-6302. DOI: 10.1007/s10570-019-02504-y
- Sikora, M., and Danielewicz, D. (2019). "Production of unitary moulded pulp products using Rapid-Köthen apparatus," *BioResources* 14(4), 9781-9785. DOI: 10.15376/biores.14.4.9781-9785
- Song, J. H., Murphy, R. J., Narayan, R., and Davies, G. B. H. (2009). "Biodegradable and compostable alternatives to conventional plastics," *Philosophical Transactions of the Royal Society B: Biological Sciences* 364, 2127-2139. DOI: 10.1098/rstb.2008.0289.
- Song, H. N., Ankerfors, M., Hoc, M., and Lindstrom, T. (2010). "Reduction of the linting and dusting propensity of newspaper using starch and microfibrillated cellulose," *Nordic Pulp & Paper Research Journal* 25(4), 495-504. DOI: 10.3183/NPPRJ-2010-25-04-p495-504.
- Sørensen, G. and Hoffmann, J. (2003). "Moisture sorption in moulded fibre trays and effect on static compression strength," *Packaging Technology and Science* 16(4), 159-169. DOI:10.1002/pts.622.
- Stierlingov, A. A. (1961). "Production of cast products from paper pulp. lexicon of paper technologist," Collective work. Gosliesbumizda Press, Moskva, Leningrad, Rosia (in Russian).
- Su, Y. Q., Yang, B., Liu, J. G., Sun, B., Cao, C. Y., Zou, X. J., Lutes, R., and He, Z. B. (2018). "Prospects for replacement of some plastics in packagings with lignocelluloses materials: A brief review," *BioResources* 13(2), 4550-4576. DOI: 10.15376/biores.13.2.Su.
- Su, J., Mosse, W. K. J., Sharman, S., Batchelor, W., and Garnier, G. (2012). "Paper strength development and recyclability with polyamideamine-epichlorohydrin (PAE)," *BioResources* 7(1), 913-924 DOI: 10.15376/biores.7.1.0913-0924.
- Sung, Y. J., Ryu, J. Y., Kim, H. J., Kim, T. K., and Song, B. K. (2004). "Improvement of drainage at wet pulp mold process," *Journal of Korea Technical Association of the Pulp and Paper Industry* 36(3), 52-59.
- Sung, Y. J., Kim, H. M., Kim, D. S., and Lee, J. Y. (2015). "Evaluation of water resistance properties of pulp mold depending on the types of raw materials and the additives," *Palpu Chongi Gisul/Journal of Korea Technical Association of the Pulp and Paper Industry* 47(5), 112-119. DOI: 10.7584/ktappi.2015.47.5.112.
- Taxology (2025). "What is the Single-Use-Plastic Directive (SUP Directive) and what obligations does it entail?," <https://taxology.co/pl/blog/dyrektywa-sup/> (in Polish).
- Tomczuk, R. (1989). "Production technology of peat pots at the paper products factory in Drezdenko," *Przegląd Papierniczy* 44(12), 407-409 (in Polish).
- Trezza, T. A., and Vergano, P. (1994). "Grease resistance of corn zein coated paper," *Journal of Food Science* 59(4), 912-915. DOI: 10.1111/j.1365-2621.1994.tb08156.x.

- Triantafillopoulos, N., and Koukoulas, A. A. (2020). "The future of single-use paper coffee cups: Current progress and outlook," *BioResources* 15(3), 7260-7287. DOI: 10.15376/biores.15.3.Triantafillopoulos
- Tweede, D., and Wever, R. (2007). "The history of molded fiber packaging: A 20th century pulp story," Thesis. TU Delft digital repository (Netherlands), 2007. International Association of Packaging Research Institutes.
- Wang, Z., Cai, Y., and Jing, Y. (2012). "Moulded pulp material structure parameters on the performance of the buffer," *Energy Procedia* 17 (Part B), 1872-1877. DOI: 10.1016/j.egypro.2012.02.325.
- Wang Z.-W., and Li, X.-F. (2014). "Effect of strain rate on cushioning properties of molded pulp products," *Materials and Design* 57, 598-607. DOI: 10.1016/j.matdes.2014.01.019.
- Wang, Q., Xiao, S., Shi, S.Q. and Cai, L. (2018). "Effect of light-delignification on mechanical, hydrophobic, and thermal properties of high-strength molded fiber materials," *Scientific Reports* 8, article 955. DOI: 10.1038/s41598-018-19623-4.
- Wang, H., Wang, J., Si, S., Wang, Q., Li, X., and Wang, S. (2021). "Residual-lignin-endowed molded pulp lunchbox with a sustained wet support strength," *Industrial Crops and Products* 170, article 113756. DOI: 10.1016/j.indcrop.2021.113756.
- Wang, Q., Xiao, S., Shi, S. Q., and Cai, L. (2019). "Mechanical property enhancement of selfbonded natural fiber material via controlling cell wall plasticity and structure," *Materials and Design* 172, article 107763. DOI: 10.1016/j.matdes.2019.107763.
- Waranyou, S. (2014). "Preparation and characterization of moulded pulp container made by hot compression moulding," *IPPTA Q. Journal Indian Pulp Technology Association* 26(2), 89-95.
- Vargas, F., González, Z., Sánchez, R., Jiménez, L., and Rodriguez, A. (2012). "Cellulose pulps of cereals as raw material for manufacture of ecological packaging," *BioResources* 7(3), 4161-4170. DOI:10.15376/biores.7.3.4161-4170.
- Xie, Q., Liu, G., Zhang, Y., Yu, J., Wang, Y., and Ma, X. (2022). "Active edible films with plant extracts: An updated review of their types, preparations, reinforcing properties, and applications in muscle foods packaging and preservation," *Critical Reviews in Food Science and Nutrition* 63(32), 1425-11447. DOI: 10.1080/10408398.2022.2092058
- Xin, G., Hongwei, J., and Haiyou, Z. (2014). "Finite element simulation of molded pulp pallet in a dropping process," *Applied Mechanics Material* 469, 209-212. DOI: 10.4028/www.scientific.net/AMM.469.209.
- Xuy (2025). https://pa.xuyemachinery.com/Special-shaped-tray-making-machine.html?campaignid=21246500363&adgroupid=160997147959&feeditemid=&targetid=kwd-4840048431&device=c&creative=698047941313&keyword=pulp%20molding%20machine&gad_source=1&gclid=EAIaIQobChMIItZfi64fDjAMVtQ-iAx3T0wJqEAAyAAEgLYcPD_BwE
- Yang, L., Pelton, R., McLellan, F., and Fairbank, M. (1999). "Factors influencing the treatment of paper with fluorochemicals for oil repellency," *TAPPI J.* 82(9), 128-135.
- Yang, X., Berthold, F., Berglund, LA. (2019). "Preserving cellulose structure: Delignified wood fibers for paper structures of high strength and transparency," *Biomacromolecules* 19(7), 3020-3029. DOI: 10.1021/acs.biomac.8b00585.
- YT (2025). https://www.youtube.com/watch?v=kgGVbyVf1_U.
- YT-2 (2025). <https://www.youtube.com/watch?v=i2f2OrRpFjY>.

- Zhang, Y., Duan, C., Bokka, S. K., and He, Z. (2022). "Molded fiber and pulp products as green and sustainable alternatives to plastics: A mini review," *Journal of Bioresources and Bioproducts* 7, 14-25. DOI: 10.1016/j.jobab.2021.10.003.
- Zhao, Y.-L., Xiao, S.-L., Yue, J.-Q., Zheng, D.-Y., and Cai, L.-P. (2020). "Effect of enzymatic hydrolysis lignin on mechanical strength and hydrophobic properties of molded fiber materials," *Holzforschung* 74(5), 469-475. DOI: 10.1515/hf-2018-0295.
- Zhou, Y., Shan, Y., Guan, D., Liang, X., Cai, Y., Liu, J., Xie, W, Xue, J., Ma, Z., and Yang, Z. (2020). "Sharing tableware reduces waste generation, emissions and water consumption in China's takeaway packaging waste dilemma," *Nature Food* 1(9), 552-561. DOI: 10.1038/s43016-020-00145-0.

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