

Design and Technology Development of an Innovative Biodegradable Single-Use Cup [†]

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[†] Presented at the 15th International Scientific Conference TechSys 2026—Engineering, Technologies and Systems, Plovdiv, Bulgaria, 14–16 May 2026.

Abstract

The presented study is dedicated to a “green” solution for hot beverage packaging—a biodegradable single-use cup. Product development follows a specifically elaborated methodology that involves initial material characterization, followed by adjusted product design. The research and design activities continue toward mold design development and testing. The study concludes with a cost analysis, in which an alternative material composition is also examined. The finalized product is ready for industrialization, reaching TRL 5, with assessed financial aspects. This study is a good demonstration of the application of modern technologies and tools for the development of an innovative product.

Keywords: single-use cup; biodegradable; zeolite; PLA

1. Introduction

Single-use cup packaging is in widespread use nowadays as a common solution for food and beverage packaging. The use of plastics for single-use packaging is dominant, resulting in a huge amount of plastic waste per year (estimated at about 9 billion tonnes of plastic, in 500 billion cups per year), mostly from fossil fuels [1,2]. The decomposition of these products is a challenge, as the average time for plastic decomposition is about 450 years [2]. The so-called disposable cups are typically made from polystyrene or polymer-lined paperboard, which are widely used as cheap, convenient packaging for hot beverages [3]. The use of disposable products is increasing exponentially due to their convenience. The search for sustainable alternatives is ongoing, as reflected in a wide variety of solutions [4]. Different solutions involve the use of matrices consisting of polymers derived from natural sources, such as polylactic acid—PLA [5], polybutylene adipate-co-terephthalate [6], chitosan [7], gelatin [8], soybean protein [9], cellulose [10], and starch [11]. The additives are used to modify the polymer structure, thereby improving packaging properties and biodegradability.

A possible solution for a biodegradable single-use hot beverage cup—the composition of zeolite and PLA—has been examined in a previous study [12]. The results of the analysis of this composition (zeolite and PLA characterizations) indicate a potential for an economic, eco-friendly, and practical hot beverage packaging [13,14]. The preliminary study of the



Academic Editors: Nikola G. Shakev, Valyo N. Nikolov, Nikolay R. Kakanakov and Sevil A. Ahmed-Shieva

Published: 4 August 2026

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technology is also positive and serves as a basis for the current research study. It shows that the focus should be set mainly on molding technologies [12].

The main target of the study is to present the development of design and mold tool for a biodegradable single-use cup, based on the above discussed composite material—zeolite and PLA. This is an important step towards providing the market with a reliable, innovative and green-based solution for beverage consumption packaging.

2. Materials and Methods

2.1. Methodology

The research and development activities are based on the sequence of steps presented in Figure 1, which are expected to result in successive product development. The process starts with two parallel activities—the first “branch” evaluates the material-specific properties (strength and hygroscopicity), while the other develops the single-use cup design. Furthermore, the cup design is updated based on the measured parameters, and the mold tool design is developed. The mold is preliminarily tested, and certain design changes are made to reach its final design [15]. The last step concerns the final assessment of the design cost and its potential for market realization.

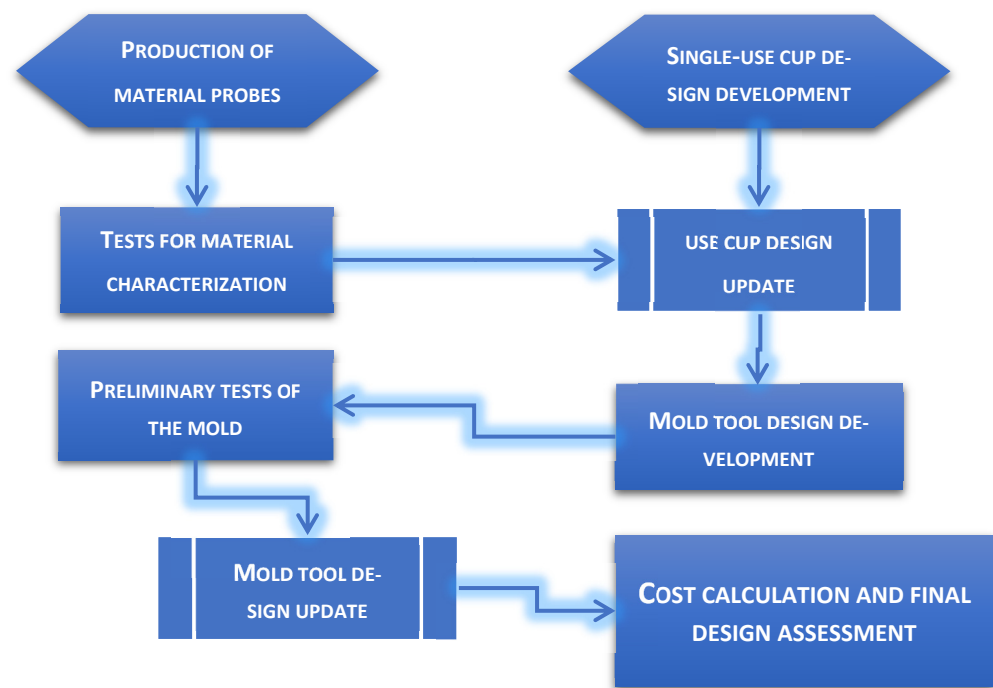


Figure 1. Methodology for single-use biodegradable design development.

2.2. Methodology for Material Characterization

The first step is to perform characterization of material properties in two directions—its mechanical strength (which is important for overall product application) and its ability to attract and hold water molecules from the surrounding environment through absorption or adsorption—hygroscopicity. Certain probes are manufactured as to perform these tests—4 probes for each test, or 8 probes in total. These probes are demonstrated in Figure 2a, where the probes used for the mechanical strength tests are shown.

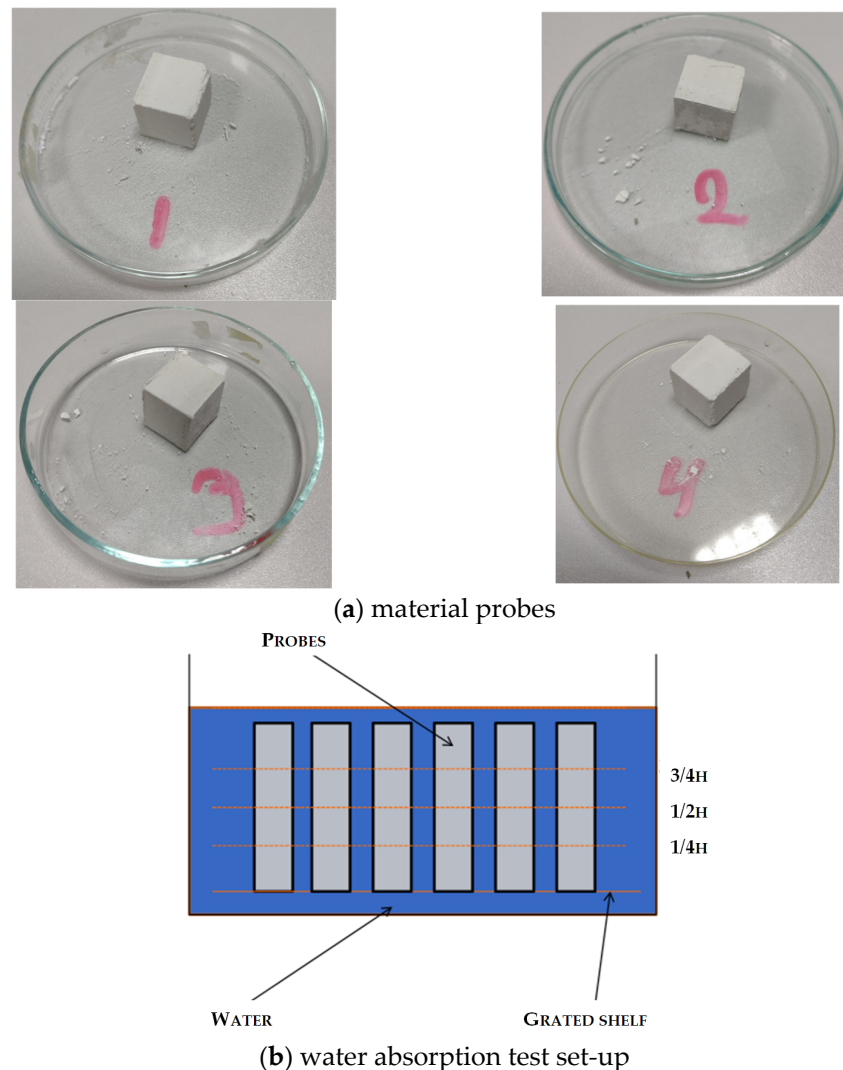


Figure 2. Single-use biodegradable design testing and development.

2.2.1. Mechanical Strength Test Methodology

Material strength is decisive for the structural strength of the future product—a cup for hot drinks. Typical methods for measuring strength usually progress in two directions—measuring tensile strength and measuring compressive strength. Compressive strength measurements place significantly lower demands on the geometry of the test tubes, since there is no need for connecting surfaces to the test equipment. This is the reason why a testing method was chosen to determine the compressive strength of the material. In this regard, the test tube is intended to be a cylindrical body. The purpose of the study is to determine with a sufficient degree of reliability the necessary force applied to the test probe to cause the specimen to break. The test probe is loaded on a press with a force that causes pressure in the specimen, with the load gradually increasing until the test probe breaks.

2.2.2. Water Absorption Test Methodology

The optimal parameters of the future technology process are the result of several repeated experiments conducted as a planned experiment. The experiment aims to provide a more detailed characterization of the hydrophysical properties of the composition, in particular, under thermal stress from a hot drink. Hydrophysical properties refer to the properties characterizing the static or cyclic effect of water or water vapor on materials. Eight hydrophysical properties are controlled, including hygroscopicity, humidity (water

content in the material), water absorption, water saturation, water resistance, capillary water absorption, water impermeability, and frost resistance. In principle, to a certain extent, these parameters are connected. The main parameter controlled in these experiments is water absorption at a given level of liquid heating.

Water absorption—marked as WA_p —is the ability of the material to absorb and retain water under the action of molecular and capillary forces at normal atmospheric pressure. Water absorption is as great as the porosity, free surface area of the pores, and hydrophilicity of the material. Water is absorbed most intensively in the initial hours, and the more heterogeneous the capillary sizes are, the greater the rate of water absorption.

Samples of the material are dried to a constant mass and weighed on a balance with an accuracy of 0.01 g. Then, they are placed in a bath on a grate so that their lower surface does not touch the bottom of the bath (see Figure 2b). At intervals of 4 to 6 h, water is poured into the bath, and the samples are immersed successively to $\frac{1}{4}$, $\frac{1}{2}$, and $\frac{3}{4}$ of their height. Finally, they are completely covered with water; the water layer above them should not exceed 2–3 cm. The gradual addition of water ensures the free escape of air trapped in the material's pores, thereby accelerating water absorption. After 3 days, the samples are removed from the water, wiped with a damp soft cloth, and weighed. To check whether the samples are fully water-saturated, they are placed in water for another 24 h and weighed again. The mass difference should not exceed 1%.

Water absorption is defined by two parameters: by mass and by volume. In this particular study, water absorption by mass was monitored, and it was calculated using the formula:

$$WA_p = \frac{m_W - m_D}{m_D} * 100, \% \quad (1)$$

where

m_W is the mass of the water-saturated sample, kg;

m_D —the mass of the dry sample, kg.

Water absorption gives an idea of the volume of pores that are filled with water under normal atmospheric conditions. The water absorption of materials varies widely: for porous thermal insulation materials with open pores, 100%; for granite, 0.02–0.07%; for adobe, 8–15%, etc.

As an additional characteristic for materials—the so-called total water absorption—is used to assess the structure of materials and is characterized by the coefficient of saturation of the pores with water— K_S :

$$K_S = \frac{WA_p}{WA_A} \quad (2)$$

where

WA_A —absolute water saturation, [%].

This coefficient varies from 0, when all pores in the material are closed, as in the case of various waterproofing, to 1, when all pores are open. The decrease in K_S at the same porosity indicates that open porosity decreases, thereby increasing the frost resistance of the materials.

Water absorption negatively affects some material properties: thermal conductivity and bulk density increase, strength and frost resistance decrease, and some materials swell.

The water absorption values were determined after successive measurements of the mass of the test tubes before and after immersion in water. The mass water absorption was determined according to the formula cited above.

2.3. Single-Use Cup Design Development and Update

The single-use biodegradable cup is planned to be produced of a material that is a mixture of a binder—PLA—and zeolite. A preliminary design has been developed, as is

shown in Figure 3. The design was updated, using obtained results from mechanical and hygroscopicity tests.

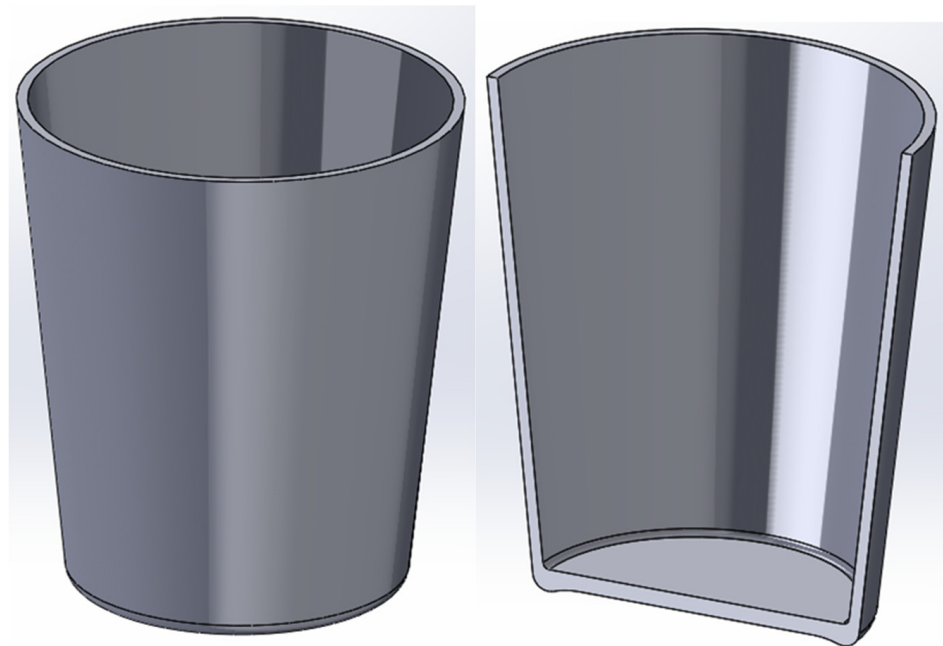


Figure 3. Single-use biodegradable design model.

2.4. Mold Design and Technology Development

The tool is a prototype—demonstrator—and is intended to develop a suitable technology for manufacturing the product. It is intended to evaluate and optimize the composition of the zeolite-binder, as well as the design of the product itself. The main requirements set at this stage of the project for the forming tool that is in development—a demonstrator type system for forming test cups—are:

- To enable the production of a real part.
- To ensure minimal cost
- To be able to modify it with minimal effort and expense, in order to optimize the wall thickness of the part and its shape.
- To be able to work with different types of product materials.
- To be able to produce a small series, in order to provide samples and establish a stationary process.

A scheme of the technological process has been created, as is presented in Figure 4. It includes seven main stages, as follows:

- Phase 1: Grinding of the material (Zeolite)—the goal is to prepare the material for its better mixing with the binder–gelatin. The zeolite is ground to the appropriate maximum size of the resulting grain structure.
- Phase 2: Dosing of the binder and dissolving in water—the gelatin is measured as a quantity, according to the desired proportion to the zeolite, then it is dissolved in water, stirring until a maximally homogeneous solution is achieved.
- Phase 3: Overheating—in this phase, the binder is overheated, in order to prepare it for mixing with the zeolite in the next stage.
- Phase 4: Mixing of the starting material and binding substance—the two components—the aqueous solution of gelatin and the ground starting material–zeolite—are mixed until a maximally homogeneous mixture is achieved.

- Phase 5: Forming—the mixture obtained in the previous phase is poured into a previously prepared mold, compacted until it occupies the corresponding volume.
- Phase 6: Heat treatment—is performed in two steps, first the mold is dried at room temperature, then it is thermally treated in a preheated oven;
- Phase 7: Remove of the obtained molds—the technological equipment is opened and the resulting product is removed.

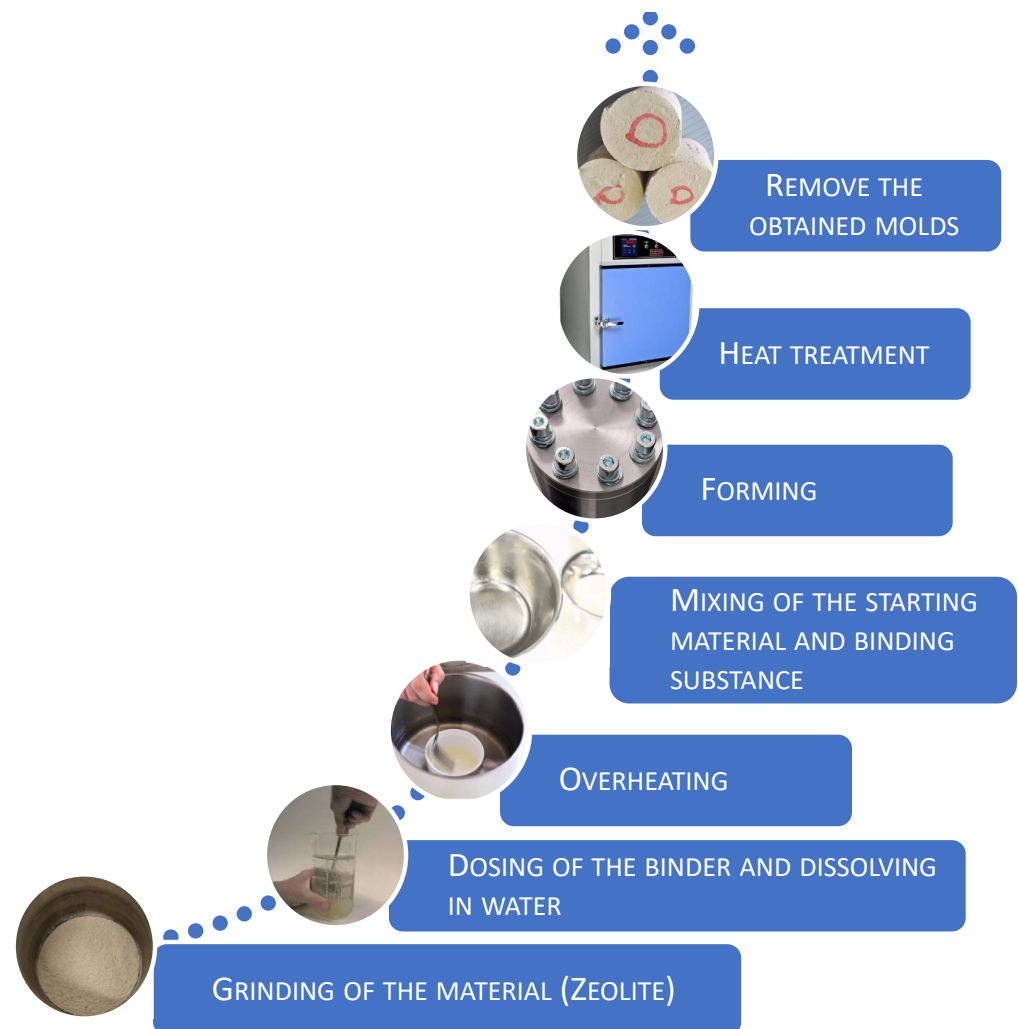


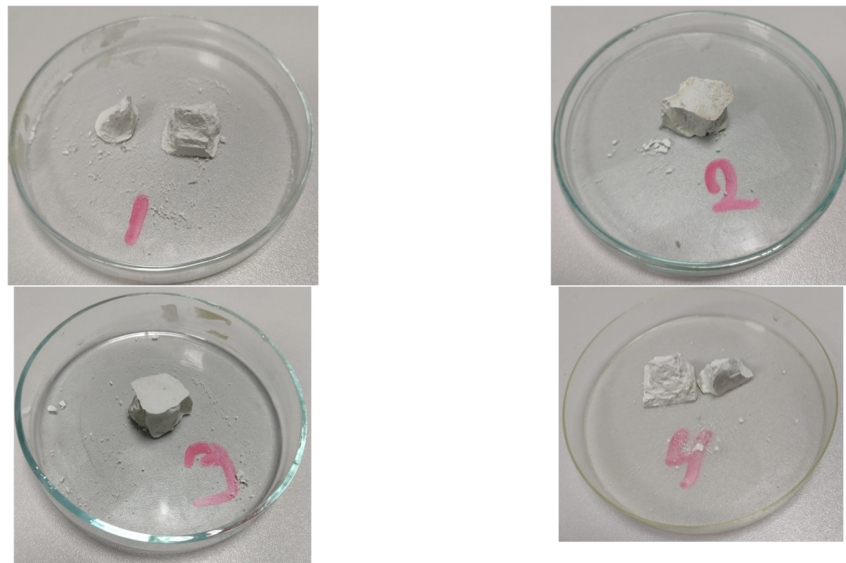
Figure 4. Single-use biodegradable design development.

3. Results

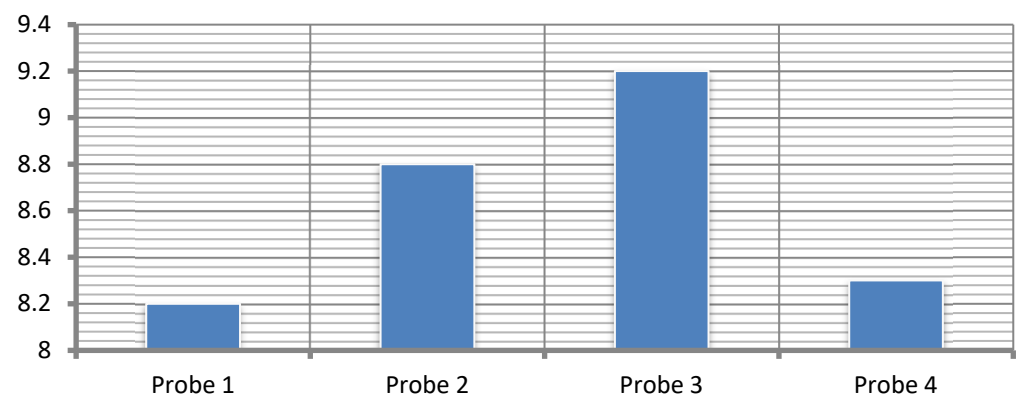
3.1. Material Characterization

3.1.1. Mechanical Strength Test

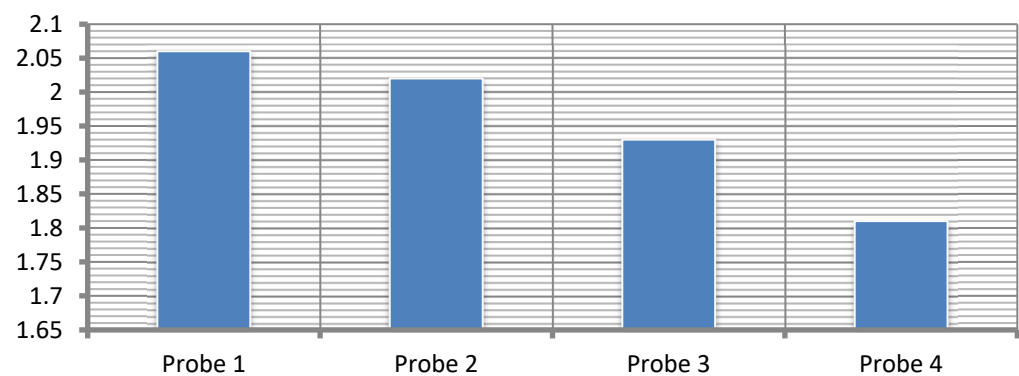
The purpose of the test is to determine with a sufficient degree of certainty the necessary force applied to the pressure of the probe, at which the destruction of the sample is achieved. The compressive strength is determined by using a press and measuring the applied compressive force, with the load gradually increasing until the destruction of the tested probe is achieved. The maximum compressive stress reached is the one at which the probe breaks. The results of the tests carried out—destroyed probes—are shown in Figure 5.



(a) Tested probes



(b) Measured stress at probe break



(c) Measured water absorption of probes

Figure 5. Results for the tested material probes.

3.1.2. Water Absorption Test

The results of the measurements are graphically compared in Figure 5. The indicated values represent the percentage increase in the mass of the test tubes for four test samples. The total deviation in the obtained results does not exceed $\pm 8\%$, which is not significant from the point of view of the absolute values for water absorption.

3.2. Mold Design Development

The requirements set, as well as the analysis of the manufacturing technology carried out in the previous phase, lead to a design of the molding tool, in which it is planned to inject the product with a direct central sprue in the bottom of the cup. For the test samples, the sprue is allowed to be removed mechanically. This is shown in Figure 6.

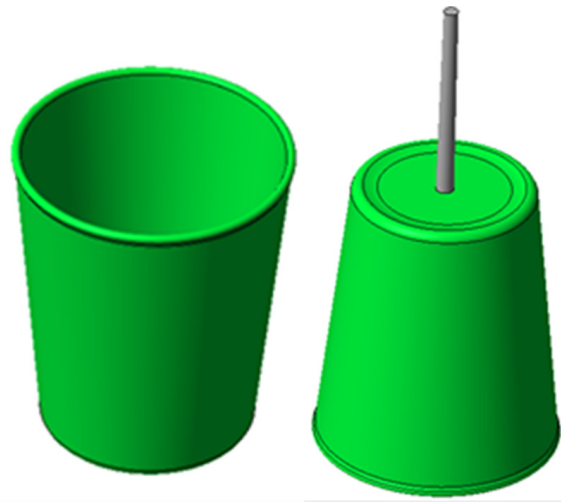


Figure 6. Test cup and product technology solution for a demonstrator system for forming test cups.

The technological analysis of the product lead to the following parameters of the machine, which are planned to be used during the injection molding of the test cup, as follows:

- Closing force 60–80 t.
- Distance between the columns—300 mm × 300 mm.

The planned machine is larger than necessary, but one of the important parameters is the ability to optimize the wall thickness, in order to reduce the cost of the product, which will require a higher specific pressure. Therefore, from this point of view, a reserve will be needed in the design of the tool, ensuring the possibility of using a larger machine than initially planned.

A detailed design of a forming tool for forming test cups has been developed. The system is applicable for both molding and injection molding of the material, which makes it suitable for a preliminary test series preceding the mass production of the developed ecological cup for hot drinks.

The design of the tool is classic with built-in forming inserts and a separate package. The package is made of purchased K and P plates. The two “frames” carrying the forming elements are made of K plates. They are responsible for ensuring the accuracy of the orientation between the two forms. The adopted K plates have precise holes and meet the requirements. The remaining plates of the package are made of type P. The lack of holes and the need to manufacture them affects the functionality of the tool to a lesser extent.

The general appearance of the assembled demonstrator system for molding test cups is shown in Figure 7. The developed virtual prototype (three-dimensional model) of the structure is shown in both its assembled form and its exploded form, which illustrates its individual components well. The manufactured mold is also shown in Figure 7, ready for its first tests.

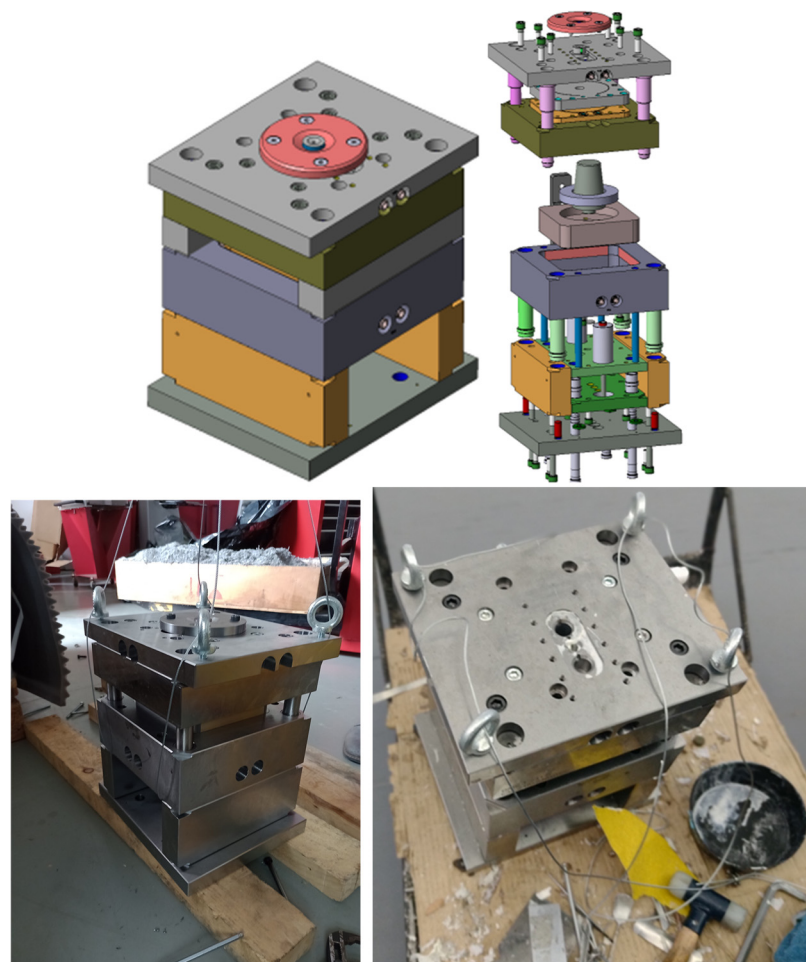


Figure 7. Finalized mold design.

3.3. Mold Design Testing, Development and Final Product

Tests have been conducted with the prototype demonstrator under various technological parameters, with these tests mainly focused on the possibilities of producing cups for hot drinks by injection molding. The tool also suggests certain possibilities that allow for increased productivity [16,17]. The tool is located in a laboratory environment, where a low-pressure injection molding method was used, without the use of a machine. The main goal is to verify the possibility of producing test samples even under such conditions, as is also assumed by the specific implementation of the project.

The mold provides a significant advantage—the possibility of two types of technologies for the production of cups for hot drinks—by molding and by injection molding. The specificity of this type of test makes it appropriate to use polylactic acid as a binder. The preparation of the tool includes coating it before use in order to make it easier to remove the resulting part. Different types of coatings were tested during this stage of mold design validation.

Parts of the conducted tests are presented as photographs of obtained samples of the test cups. As is visible in Figure 8, the experimental sample shows certain problems with the selected technological parameters, which lead to underfilling of the mold. The merge lines and the unfilled part are clearly visible, which requires correction of the technological parameters. The method of feeding the material through the bottom of the cup requires a certain use of an injection molding machine operating at a suitably selected material injection pressure [18]. In practice, free injection through the tool hole is expected to

lead, in most cases, to the observed result shown by the obtained test samples from the preliminary tests.



Figure 8. Initial tests results for mold design and production technology specifics.

The next step in the product development process is related to the improvement of the mold as to reach a successful production. In this sense, the forming tool (prototype demonstrator) was used to form test samples of cups. A total of 15 samples were made, which were subsequently used to adjust technology parameters settings. The final product has a good performance and outfit.

3.4. Cost Assessment of the Developed Product

Achieving optimal cost for each product is crucial for it to be competitive in the market. At the earliest stage, at the conceptual level, it is possible to vary most parameters. It is for this reason that the cost estimate of a biodegradable cup for hot drinks is of great importance at the earliest possible stage.

The calculation is made based on the geometry of a cup for hot drinks developed and shown in Figure 3. The presented geometry has a volume of 28.2 cm^3 . The cost price is determined for two types of forming tools—the manufactured forming tool (prototype demonstrator) and a high-performance (multi-cavity) forming tool, effective and suitable in the case of mass production. The economic assessment of the multi-cavity tool is expert, based on the real data for the tool implemented under the project for the production of 1 piece of hot beverage cup (prototype demonstrator).

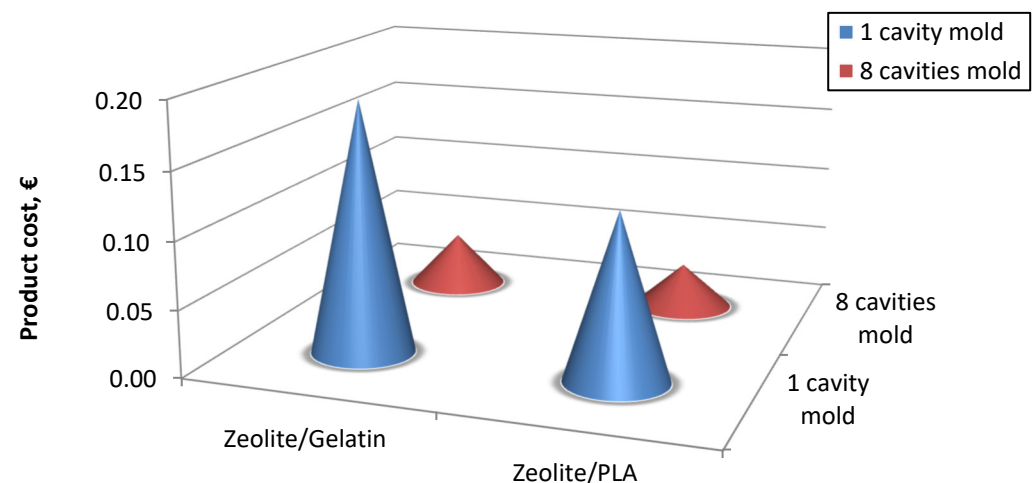
Initially, a detailed estimate of the costs forming the cost price of the machine was made. This determination was based on the previously determined estimated cost prices of the machine components (based on analog parts or on precisely determined production costs, as well as on market prices of purchased components). The cost price of the prototype, which was partially performed by a subcontractor, played a key role in determining these reference values, taking into account the potential difference in serial production compared to the prototype unit. The results of the economic assessment for the production of cups with a composition of zeolite and PLA are summarized in Table 1.

Achieving optimal cost is crucial for a product. In the first steps of concept and design, the freedom to vary the parameters is greatest, while in the subsequent stages, design decisions are highly limited [19]. The optimization of cost occurs through technological solutions, tools and material suppliers, as well as in terms of technological equipment. All these factors are taken into account when determining the level of optimization.

A comparison of the cost of four variants of the implementation of a biodegradable cup for hot drinks, varying between a single and multi-cavity forming tool, as well as the use of gelatin or polylactic acid as a binder, was conducted. This comparison is evident in Figure 9.

Table 1. Cost estimation.

Component		Value	
Mold			
Number of cavities, nbr		1	8
Cost of original components, €		3989.08	21,541.02
Cost of supplied components, €		462.05	2079.23
Cost of standard components, €		29.13	112.14
Design/Assembly/Tests		2400.00	11,700.00
Total cost of the mold, €		6880.26	35,432.39
Lifetime capacity, nbr		300,000	8,000,000
Single product mold cost (1 cup), €		0.023	0.004
Production expenses			
Technology equipment expense per hour, €/h		22.00	28.5
Production per hour, nbr/h		300	2215
Production expenses (1 cup), €		0.073	0.013
Material expenses			
	Quantity, kg	Cost per kg, €/kg	Cost per piece, €
Zeolite	0.0557	0.1026	0.0057
Binder	0.0038	1.7103	0.0065
Material expenses per single cup			0.012
Other expenses			
Other direct expenses, %		15	
Total cost per cup, €		0.125	0.034

**Figure 9.** Financial comparison of product variants, based on material composition.

The comparison made between the individual variants in terms of their total cost indicates the following:

- (1) Significant reduction in cost when choosing a multi-cavity (8-cavity) tool;
- (2) Reduction in the cost when using polylactic acid as a binder.

The option of execution with a PLA binder, produced by a multi-cavity tool, was clearly chosen as the optimal one from an economic point of view. This option is subject to further economic optimization, which, however, does not exclude the use of gelatin as a binder. The main assumption in the optimization carried out is the definitive use of a multi-cavity molding tool, which is required by the significant difference in cost.

The research on the optimization of the technical and economic efficiency of the series is focused on the following main areas:

- Optimization of the costs of technological equipment: this optimization is mainly aimed at increasing the resource of the forming tool. The expert assessment of the tool

indicates its use within 1,000,000 cycles, which was used in the detailed calculations of the product cost conducted above. The resource determined in this way can be increased up to two times, when using appropriate technologies and heat treatment modes of the contact surfaces.

- Opportunities for reducing production costs: The following more important opportunities are considered:
 - To reduce the technological time of one production cycle.
 - Reducing the costs for 1 machine hour.
- Geometric optimization of the product in order to reduce material costs.

4. Conclusions

The performed studies show that the concept of a zeolite-based biodegradable cup for hot beverages is a viable solution. Following the elaborated methodology, the steps as material characterization by testing, product design development, mold design and its testing, and ending with financial assessment lead to a definitive design of a cup. The cup is based on a composition of zeolite and PLA and is expected to be concurrent on the international market, reaching its validation in laboratory environment (TRL 5). The design, as well as production technology, are matured, and further steps would require multi-cavity mold design and production, and production setup.

Author Contributions: Conceptualization, K.K. and G.C.; methodology, G.C. and M.I.; software, M.S.; validation, K.K., M.I. and M.S.; formal analysis, M.S.; investigation, K.K. and M.I.; resources, G.C. and M.I.; data curation, G.C. and M.S.; writing—original draft preparation, K.K.; writing—review and editing, G.C. and K.K.; visualization, M.S.; supervision, K.K.; project administration, M.I. and M.S.; funding acquisition, M.I. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by European Regional Development Fund under “Research Innovation and Digitization for Smart Transformation” program 2021–2027 under the Project BG16RFPR002-1.014-0006 “National Centre of Excellence Mechatronics and Clean Technologies”.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data are contained within the article.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

TRL	Technology Readiness Level
PLA	Polylactic acid
WA	Water absorption

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