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Development of Biodegradable Cups from Corn and Fruit Processing Waste and Its Characterization: A Sustainable Approach

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Abstract

Single-use plastic cups and packaging materials pose severe environmental challenges due to their persistent nature and harmful impact on ecosystems and wildlife. Simultaneously, the indiscriminate disposal and burning of agricultural and food processing biomass contribute significantly to pollution. Among this biomass, waste generated from corn and fruit processing is produced in substantial quantities and is rich in natural fibres, making it a potential source for developing biodegradable products. This study focuses on the development of biodegradable cups using corn cob powder, mango peel powder, and pineapple peel powder through hot-press compression and moulding technology. The formulation was optimized using response surface methodology, with independent variables, i.e., corn cob (20–40 g), mango peel (30–50 g), and pineapple peel (20–30 g). The responses evaluated including hardness, colour (L* value), and water-holding capacity. The model was fitted using a second-order polynomial equation. Optimum results were achieved with 34 g of corn cob, 40 g of mango peel, and 26 g of pineapple peel powder, yielding a maximum hardness of 2.41 kg, an L* value of 47.03, and a water-holding capacity of 18.25 min. The optimized samples further underwent characterization of physical properties, functional groups, lattice structure, surface morphology, and biodegradability. Colour parameters were recorded as L* = 47.03 ± 0.021, a* = 10.47 ± 0.041, and b* = 24.77 ± 0.032. Textural study revealed a hardness of 2.411 ± 0.063 and a fracturability of 2.635 ± 0.033. The developed biodegradable cup had a semicrystalline nature with a crystallinity index of 44.4%. Soil burial tests confirmed that the developed cups degraded completely within 30 days. These findings highlight the potential of corn and fruit processing waste for developing eco-friendly, biodegradable cups as sustainable alternatives to single-use plastics.

Keywords: biodegradable cups; ecofriendly; optimization; processing waste; response surface methodology

Academic Editor: Zhaobin Qiu

Received: 11 September 2025
Revised: 8 October 2025
Accepted: 31 October 2025
Published: 4 November 2025

Citation: Wandhekar, S.S.; Kshirsagar, R.B.; Sadawarte, S.K.; Gosavi, R.A.; Gabor, V.; Shaikh, A.M.; Bela, K. Development of Biodegradable Cups from Corn and Fruit Processing Waste and Its Characterization: A Sustainable Approach. *Macromol* **2025**, *5*, 53. https://doi.org/10.3390/macromol5040053

1. Introduction

The food packaging sector contributes 36–40% of plastic waste production, leading to pollution of water and landfill resources worldwide, as it takes more than a hundred years to degrade and leaches harmful chemical residues into the soil and water [1,2]. Considering the impact of single-use plastic items, there is a growing need for alternative solutions to plastic plates, bowls, cups, straws, and spoons. One million tons of plastic waste is generated annually, with food packaging constituting a significant portion of single-use items [3,4]. These plastic items break down into smaller pieces known as microplastics, which enter the ecosystem and indirectly enter human bodies through the consumption of food [5]. Consumption of hot food products in single-use plastic tableware is unhealthy because heat causes harmful chemicals like bisphenol-A, phthalates, and styrene to leach from the plastic into the food or drink [6]. These chemicals are endocrine disruptors that can interfere with hormone balance, leading to risks such as heart problems, hormonal disorders, and reproductive issues. Additionally, microplastics released from heated plastics may affect gut health and potentially lead to inflammation and other health complications [6]. However, single-use plastic cups are mostly used for the consumption of tea, coffee, soup, and ice cream, and they pose a serious environmental threat due to their accumulation in the environment after use [7]. The production of these cups relies on petroleum, generating greenhouse gas emissions and depleting resources. Recycling options are limited due to contamination and material complexity, resulting in most cups ending up in landfills [4].

The global market for biodegradable cups is expanding due to rising consumer awareness, regulatory actions to curb single-use plastics, and continued technological innovation [8]. Significant advancements have been made in the development of biodegradable cups using agricultural residues such as corn husks; fruit peels, including pomegranate, citrus, and watermelon; sugarcane bagasse; wheat bran; and other plant-based biomass [9,10]. The utilization of agricultural and food processing waste to develop biodegradable packaging items is a promising approach to address the issue caused by petroleum-based plastics. The overall plastic footprint of industries can be significantly reduced by replacing conventional plastics with biodegradable alternatives from agricultural waste. This transition will facilitate waste management and sustainable agricultural practices [11]. Research institutes and industries have developed biodegradable tableware from agricultural waste with the combination of biomass such as sugarcane bagasse, wheat bran, rice husk, areca nut, banana leaves and stems, coconut shell, coir, and byproducts from food processing [12]. These tableware items can be used for various food items and liquid products while decomposing into soil and water within a few days, providing a sustainable solution.

Corn (maize) is an important cereal grain that is produced globally. The corn ear consists of kernels, cobs, husks, and silk. The corn cob is the cylindrical core portion where the kernels are attached. It is a major byproduct that constitutes 15–18% of the whole corn ear, which is generated during processing [13]. Annually, 159 million tons of corn cobs are generated during the production of different products from corn [14]. After processing, corn cob leftovers are either left in the field, given as feed to animals, or burned, causing pollution. This waste presents a significant opportunity for developing sustainable packaging materials. Corn cobs have a good chemical composition and are suitable for applications in the packaging industry [15]. They are composed of fibres, crude proteins, and minerals. In terms of dietary fibre, they are a rich source of cellulose (34–35%), hemicellulose (28–30%), and lignin (20–25%). Cellulose improves strength and facilitates the rate of degradation [16]. Lignocellulosic material from corn helps to reduce the dependency on fossil fuels compared to conventional packaging.

Fruit processing waste presents a significant global challenge, particularly in India, where the agricultural sector generates substantial volumes of waste. Fruit processing generates 20–35% waste in the form of peels, leaves, stalks, and seeds [17]. This waste has several environmental impacts upon dumping and improper disposal methods, leading to soil and water contamination. Fruit processing waste is a good source of bioactive components, antioxidants, dietary fibre, vitamins, minerals, and enzymes [18]. Mango processing generates 20–25% waste in the form of peels and kernels. Mango peel contains bioactive components, antioxidants, dietary fibres consisting of cellulose (25–27%), hemicellulose (28–30%), and lignin (13–15%), and enzymes, making it useful for the development of sustainable packaging materials [19]. Pineapple processing generates a significant amount of waste (40–45%) in the form of peels and crowns. Pineapple peel contains bioactive components, dietary fibres such as cellulose (28–30%), hemicellulose (20–23%), and lignin (16–18%), and proteolytic enzymes. These compositions make pineapple waste suitable for developing sustainable packaging solutions and biodegradable tableware [20]. Overall, the substantial waste generated from fruit processing not only poses environmental challenges but also offers significant opportunities for innovation by converting bioactive components into valuable resources, thereby promoting a circular economy and reducing food waste.

Corn and fruit processing wastes, including corn cob, mango peel, and pineapple peel, represent viable and scalable resources for the development of biodegradable cups, offering significant environmental advantages and sustainable startup opportunities. Accordingly, this study was undertaken to utilize processing waste effectively in the development of biodegradable cups. The optimization of independent variables based on the response variable was achieved through response surface methodology, specifically employing Design Expert software with a Box–Behnken design. Product development was carried out with the application of advanced compression moulding technology. Comprehensive characterization of the optimized product was conducted, encompassing texture analysis, colour measurement, water-holding capacity, dimensional evaluation, functional group analysis, morphological assessment, and biodegradability testing. This approach presents an environmentally responsible alternative for biodegradable cup production, while simultaneously addressing ecological concerns associated with conventional plastics and agro-processing waste biomass.

2. Materials and Methods

2.1. Materials

Corn cobs were obtained from the corn processing mill in Ahilyanagar, Maharashtra, India. Mango and pineapple peels were sourced from the processing industries in Pune, India. Corn starch was obtained from Civita Food Ltd., 4275 Monostorpályi, Hungary.

2.2. Methods

2.2.1. Raw Material Preparation

Mango and pineapple peels were collected and cleaned by washing with water to remove foreign material, the waxy layer, and remaining pulp stuck to the peels. The water was drained, and the peels were cut into small pieces. The prepared pieces of peel were dried in a cabinet tray drier (Suprashesh™, AA/074/10) at 60 °C for 5 h. Dried mango and pineapple peels were converted into powder form using a grinder (Butterfly pestle 3J). The collected corn cobs were broken into small pieces and converted into powder form. The raw material in powder form was packed in a PET jar and kept dry for further experiments.

2.2.2. Experimental Design

Three independent variables were used in this study, namely corn cob (A), mango peel (B), and pineapple peel (C). Seventeen experimental combinations were generated through a Box–Behnken design (BBD) in Design-Expert software (Version 13), enabling a systematic exploration of the effects of the selected variables. The RSM method was used to optimize the statistical experimental design of the experimental process, to evaluate the interaction between individual factor variables, and to optimize the three variables of the solution. Quadratic models were developed using response surface methodology (RSM) to investigate the synergistic effects of the ingredients on key quality responses, including hardness (kg), colour (L* value), and water-holding capacity (WHC, min). The experimental ranges and levels of the independent variables in coded and actual units presented in Table 1 were corn cob (20–40 g), mango peel powder (30–50 g), and pineapple peel powder (20–30 g). The experimental batches were prepared as listed in Table 2, and three responses were studied. The centre-point experiment was repeated five times to calculate the reproducibility of the method. The Design Expert software was used for all statistical analyses, including analysis of variance (ANOVA) for models, and each response variable was verified for its significance by two-way ANOVA at the 1% level of significance ($p < 0.01$) and 5% level of significance ($p < 0.05$). A second-order polynomial equation of the following form was assumed to relate the response Y and factors:

$$Y = s_0 + s_1A + s_2B + s_3C + s_{12}AB + s_{13}AC + s_{23}BC + s_{11}A^2 + s_{22}B^2 + s_{33}C^2 \quad (1)$$

where Y is the predicted response and s_0 is a constant. Linear effects are represented by s_1, s_2, and s_3; interaction effects by s_{12}, s_{13}, and s_{23}; and quadratic effects by s_{11}, s_{22}, and s_{33}. The goals of maximum hardness, higher L value, and higher water-holding capacity were fixed for optimization. The desirability function scale is based on Derringer's concept, which ranges from 0 to 1 [21].

Table 1. Experimental ranges and levels of independent variables.

Variables	Range of Levels (g)					
	Actual	Coded	Actual	Coded	Actual	Coded
A (Corn cob)	20	−1	30	0	40	1
B (Mango peel)	30	−1	40	0	50	1
C (Pineapple peel	20	−1	25	0	30	1

Table 2. Experimental design for the biodegradable cups from corn cob powder, mango peel powder, and pineapple peel powder.

Run Order	CC (A)	MP (B)	PP (C)	Hardness (Kg)	Colour (L* Value)	WHC (min)
1	40 (1)	40 (0)	30 (1)	2.531	45.00	16
2	30 (0)	40 (0)	25 (0)	2.308	46.03	18
3	20 (−1)	30 (−1)	25 (0)	1.540	36.30	14
4	30 (0)	50 (1)	30 (1)	2.256	43.23	13
5	20 (−1)	40 (0)	20 (−1)	1.673	37.35	12.3
6	30 (0)	30 (−1)	20 (−1)	1.723	38.23	13
7	30 (0)	40 (0)	25 (0)	2.216	46.86	19

Table 2. *Cont.*

Run Order	CC (A)	MP (B)	PP (C)	Hardness (Kg)	Colour (L* Value)	WHC (min)
8	30 (0)	40 (0)	25 (0)	2.401	46.13	18
9	30 (0)	40 (0)	25 (0)	2.360	45.92	19
10	40 (1)	30 (−1)	25 (0)	1.623	43.25	17
11	40 (1)	50 (1)	25 (0)	1.823	39.23	16
12	20 (−1)	50 (1)	25 (0)	1.621	39.76	12
13	30 (0)	30 (−1)	30 (1)	2.132	42.08	17
14	40 (1)	40 (0)	20 (−1)	2.203	41.12	16.3
15	20 (−1)	40 (0)	30 (1)	1.634	39.13	14
16	30 (0)	50 (1)	20 (−1)	1.974	39.56	15
17	30 (0)	40 (0)	25 (0)	2.556	47.06	19

CC = corn cob powder; MP = mango peel powder; PP = pineapple peel powder.

2.2.3. Development of Cups

Corn cob, mango peel, and pineapple peel powders were incorporated in proportions defined by the experimental design, with 5% corn starch added to each formulation as a binding agent. The prepared formulation was mixed in a kneader with the addition of 20% water. Fifty grams of material was compressed using hot press technology available at Civita Food, Hungary, at pressures of 5 bar and 160 °C for 4 min. After that, the developed cups were removed from the top cavity of the mould.

2.2.4. Characterization

Texture Analysis

The hardness and fracturability of the prepared cups were measured using TA.XT Plus Texture Analyzer, Stable Micro System (Metron Kft). Parameters were evaluated by penetrating a 2 mm cylinder probe (P/2) on a heavy-duty platform (HDP/90) with a holed plate, using a 5 kg load cell. The texture analyser was set at a pre-test speed of 1 mm/s, a test speed of 0.5, a post-test speed of 10 mm/s, a distance of 5 mm, a trigger force of 5 g, and a data-acquisition rate of 400 pps.

Colour Analysis

The colour properties of biodegradable cups were evaluated by Hunter colour lab (Konica Miniolta CR-20, Konica Miniolta, Tokyo, Japan). Parameters such as lightness (L*, 0 for black and 100 for white), red–green (a*, [-] green and [+] red), and yellow–blue (b*, [-] blue and [+] yellow) were measured [22].

Water-Holding Capacity

The water-holding capacity of the prepared biodegradable cups was measured by filling the cups with hot water at a temperature of 100 °C, and the time was calculated in minutes before it started to leak [23]. Hot water is used as a testing fluid to ensure the performance and stability of prepared cups for serving hot fluids like tea, coffee, and soup.

Physical and Dimensional Analysis

The weight of the prepared cups was measured using a weighing balance. The thickness, diameter (internal, external, and bottom), height, and depth were measured using a Vernier calliper.

Fourier Transform Infrared Spectroscopy (FTIR)

The FTIR spectra were examined to observe the functional groups. FTIR spectra were obtained using a thermos electron corporation spectrophotometer (model-N ICOLET-5700 FTIR, USA). Spectra were recorded in a scanning range of 400–4000 cm^{-1} wavenumber.

X-Ray Diffraction (XRD)

The crystallinity index and structural characteristics of the developed biodegradable cup was analysed using a powder X-ray diffractometer (Malvern PANalytical, Malvern, UK). X-Ray diffraction patterns were recorded within a 2θ angular range of 10° to 90°, employing Cu Kα radiation with a wavelength of 1.5418 Å at a voltage of 30 kV and 15 mA current. The crystallinity percentage was calculated by the formula given by Muralidharan et al. [23].

Scanning Electron Microscopy

The cross-sectional microstructure and surface morphology of the biodegradable cups were examined using scanning electron microscopy (JSM-6510, Oxford Instruments, UK). The cup sample was coated with a 10 nm platinum coater (JEOL JFC 1600 Auto Fine Coater, JEOL, Tokyo, Japan). Imaging was performed at an accelerating voltage of 10 kV under high vacuum conditions [21].

Biodegradability Testing by Soil Burial Test

Biodegradation studies of prepared cups were carried out using a soil burial test and calculating the percentage weight loss [24]. A plastic container with holes at the bottom and on the body was selected for proper water and air circulation. The wet soil was kept in a container; cup samples were cut (3 × 4 cm), buried in soil at 8 cm depth, and maintained at room temperature. The samples were retrieved periodically after five days to observe degradation. The samples were washed, dried, and weighed, and the percentage weight loss was calculated by measuring the initial and final weights.

2.2.5. Statistical Analysis

Ingredient levels were optimized using Design-Expert software version 13. The obtained results are represented as the mean and standard deviation using Microsoft Excel. Graphs were plotted using the Origin Pro Software 8.5.

3. Results and Discussion

3.1. Effect of Various Independent Variables on Responses and Predictive Model

The experimental values of the response variables for different formulations of corn cob powder (CC), mango peel powder (MP), and pineapple peel powder (PP) are presented in Table 2. Biodegradable cups were prepared according to a previously described methodology.

3.1.1. Effect of Independent Variables on Hardness of Cups

From the obtained results, it was observed that the hardness of the prepared cup samples ranged from 1.540 kg to 2.556 kg. The ANOVA data in Table 3 reveal that the model was significant. The coefficients of linear terms, interaction, and the quadratic terms were significant at the 5% level of significance. The second-order polynomial equation presented in Equation (2) describes the effect of independent variables, that is, corn cob powder (A), mango peel powder (B), and pineapple peel powder (C), on the hardness of the cups.

$$Hardness = +2.37 + 0.214A + 0.082B + 0.1225C + 0.0298AB + 0.0918AC - 0.0318BC - 0.3637A^2 - 0.3527B^2 + 0.0058C^2 \ (R^2 = 0.8747) \ldots .. \quad (2)$$

Table 3. ANOVA and model statistics of responses for biodegradable cups.

Source	Hardness (Kg)		Colour (L* Value)		WHC (Min)	
	F Value	*p* Value	F Value	*p* Value	F Value	*p* Value
Model	5.43	0.0182	39.5	0.0001	47.66	0.0001
(A): CC	10.36	0.0147	56.83	0.0001	98.91	0.0001
(B): MP	1.52	0.2572	0.8123	0.3974	14.63	0.0065
(C): PP	3.39	0.1079	38.28	0.0005	6.77	0.0354
AB	0.1001	0.7609	24.66	0.0016	1.17	0.3151
AC	0.9522	0.3617	1.94	0.2059	4.68	0.0672
BC	0.114	0.7455	0.0143	0.9082	42.14	0.0003
A^2	15.75	0.0054	88.09	0.0001	67.47	0.0001
B^2	14.81	0.0063	81.81	0.0001	78.86	0.0001
C^2	0.004	0.9515	39.43	0.0004	86.94	0.0001
LOF	3.89 ^{NS}	0.1113	3.54 ^{NS}	0.127	0.3278 ^{NS}	0.8068
R^2	0.8747		0.9807		0.9839	
Adj.R^2	0.7135		0.9559		0.9633	
Pre. R^2	0.5434		0.7674		0.9292	
CV (%)	9.25		1.79		2.92	

LOF = Lack of fit; NS = Not significant; CV = Coefficient of variation.

The positive coefficients for the linear terms of corn cob powder (A), mango peel powder (B), pineapple peel powder (C), interaction terms (AB) and (AC), and quadratic term of pineapple peel powder (C) indicated an increase in hardness with an increase in this variable, whereas the negative coefficients of the interaction term (BC) and quadratic terms of corn cob powder (A) and mango peel powder (B) suggested that an excessive increase in these variables resulted in a decrease in hardness. The magnitude of the coefficient of the linear term showed that corn cob powder had the greatest influence on the hardness of the sample, followed by pineapple peel powder and mango peel powder. The coefficient of correlation (R^2) indicated that the developed model for hardness adequately explained 87.47% of the total variation. The lack-of-fit F-value was not significant for the obtained model. The difference between the adjusted R^2 and predicted R^2 was less than 0.2, which is in reasonable agreement. Figure 1a shows that hardness increased with an increase in the independent variables up to the optimum level, and further hardness decreased with higher levels of independent variables, which may be due to an increase in the sugar and fibre composition of fruit peels, leading to structural interference [25].

3.1.2. Effect of Independent Variables on Colour (L*) Value of Cups

The L* values of the prepared cups were measured to quantitatively assess surface colour, as this parameter is highly sensitive to compositional variations including the type and concentration of ingredients, additives, and processing methods. The L* value specifically indicates the lightness or darkness of the samples, and changes in L* can directly influence consumer perception and acceptance by reflecting visual qualities associated with

product quality [26]. From Table 2, it can be observed that the L* value ranges from 36.30 to 47.06. The results showed that the prepared cup samples were dark in shade. ANOVA showed that the model was significant, and the coefficients of the linear terms, interaction terms, and quadratic terms were also significant. A second-order polynomial equation describing the effect of independent variables, that is, corn cob (A), mango peel (B), and pineapple peel (C), on the L* value of cups is presented in Equation (3).

$$L * value = +46.4 + 2.01A + 0.24B + 1.65C - 1.87AB + 0.525AC \\ -0.045BC - 3.45A^2 - 3.32B^2 - 2.3C^2 \left(R^2 = 0.9807\right) \ldots .. \quad (3)$$

The above equation highlights the individual effects of the independent variable on the L* value of the cup samples. Positive signs with respect to the linear term (A, B, and C) and interaction term (AC) indicated an increase in the L* value with an increase in the level of the independent variable, whereas the negative sign of the interaction terms (AB and BC) and quadratic terms suggested that an excessive increase in the levels of independent variables resulted in a decrease in the L* value. The magnitude of the coefficient of the linear terms of the model revealed that corn cob was the most influential factor, followed by pineapple peel powder and mango peel powder. The coefficient of correlation (R^2) indicated that the developed model for the L* value adequately explained 98.07% of the total variation. The lack-of-fit F-value was not significant for the obtained model. The difference between the adjusted R^2 and predicted R^2 was less than 0.2, which is in reasonable agreement. From Figure 1b, it was revealed that the L* value increased with an increase in the independent variables up to the optimum level and further decreased with higher levels of independent variables showing a darker colour of cups, which may have occurred due to the presence of sugar components and chemical changes with the application of high temperature during compression as a result of the Maillard reaction [27–29].

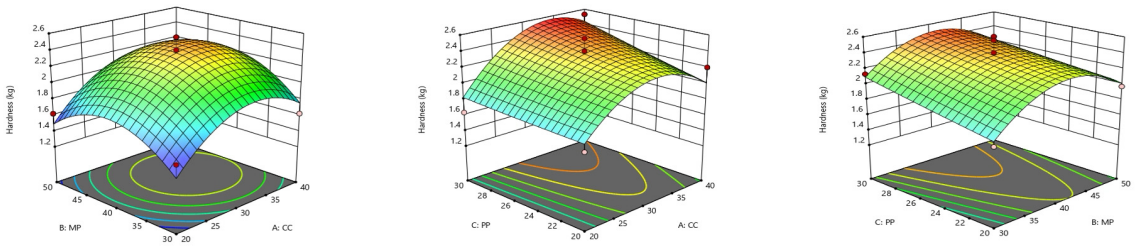
3.1.3. Effect of Independent Variables on Water-Holding Capacity of Cups

Water-holding capacity (WHC) is important for measuring how long cups can retain liquid beverages without leakage. The WHC of the prepared cups ranged from 12 min to 19 min. The ANOVA results revealed that the design model was significant. The effect of the independent variables is presented by the second-order polynomial equation given in Equation (4) below:

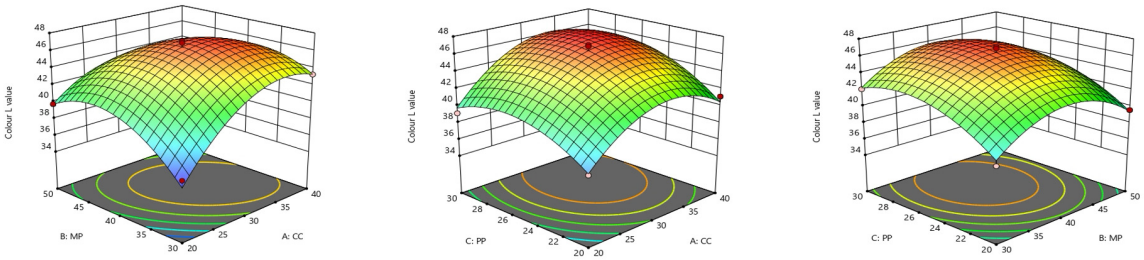
$$WHC = +18.6 + 1.63A - 0.625B + 0.425C + 0.25AB - 0.5AC - 1.5BC \\ -1.85A^2 - 2B^2 - 2.1C^2 \left(R^2 = 0.9839\right) \ldots .. \quad (4)$$

From the above equation, positive signs for the linear terms of corn cob (A), pineapple peel powder (C), and interaction term (AB) showed an increase in the WHC with an increase in the level of ingredients, whereas a negative sign for the linear term of mango peel (B), interaction terms (AC and BC), and negative signs for all quadratic terms of independent variables showed a decrease in the WHC with an increase in the levels of ingredients. The magnitude of the coefficient of linear terms of the model revealed that corn cob was the most influential factor, followed by mango peel powder and pineapple peel powder, for the WHC of biodegradable cups. The R^2 value indicated that the developed model for WHC adequately explained 98.07% of the total variation. For the obtained model, the lack-of-fit F-value was not significant. The difference between the adjusted R^2 and predicted R^2 was less than 0.2, which is in reasonable agreement. Figure 1c shows that the water-holding capacity increased with an increase in the independent variables up to the optimum level, and further decreased with higher levels of independent variables. This might be due to

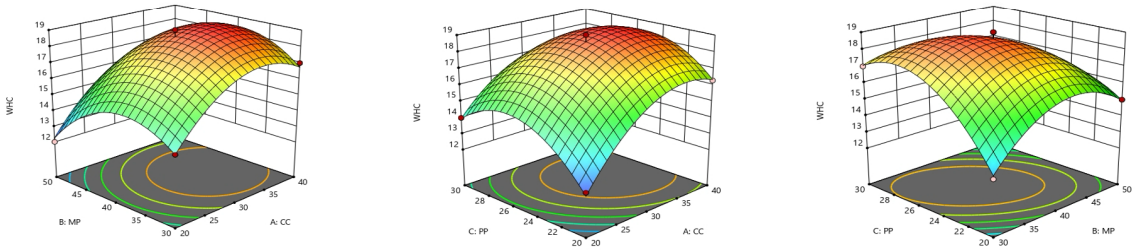
structural modifications and the fibre and sugar composition of mango peel and pineapple peel powder, making them hygroscopic in nature due to weaker bonding [30].



(a) Effect of independent variables on hardness



(b) Effect of independent variables on colour L* value



(c) Effect of independent variables on water holding capacity

Figure 1. Effect of independent variables corn cob powder (CC), mango peel powder (MP), and pineapple peel powder (PP) on responses (**a**) hardness, (**b**) colour L* value, and (**c**) water-holding capacity of biodegradable cups.

3.2. Prediction and Validation

A numerical optimization technique was used to optimize the independent parameters of biodegradable cups. For the development of biodegradable cups, the ingredient levels were optimized based on the maximum hardness, higher L* value, and higher water-holding capacity (WHC) by considering important aspects in the development of the product. The solutions were found to obtain the maximum desirability with the given criteria. The best solution, with a desirability of 0.955, was taken as the optimized ingredient level, as shown in Figure 2. The optimal combination of independent parameters which yielded biodegradable cups of the desired quality was when the composition contained 34 g of corn cob powder, 40 g of mango peel powder, and 26 g of pineapple peel powder. Predicted optimum ingredient levels as well as responses were validated by carrying out the actual experiment. The predicted values of the responses were a hardness of 2.45 kg, an L* value of 47.05, and a water-holding capacity of 18.7 min, whereas the experimental values were a hardness of 2.41 kg, an L* value of 47.03, and a water-holding capacity of 18.25 min. From Table 4, it was found that the predicted and experimental values were in close conformity. The study revealed that the fitted models were suitable for predicting the response.

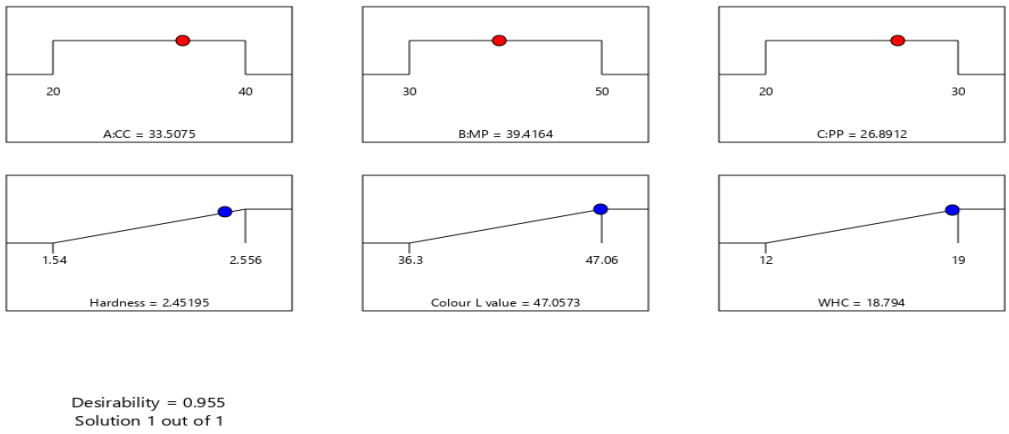


Figure 2. Graphical representation of optimized levels of independent variables and responses.

Table 4. Predicted and experimental values of responses for the prepared cup.

Responses	Predicted Values	Experimental Values
Hardness	2.45	2.41
L* value	47.05	47.03
WHC	18.7	18.25

3.3. Characterization

3.3.1. Dimensional Analysis

The prepared cups are shown in Figure 3 along with their front and top views. The weight, thickness, diameter, height, and depth of each cup were measured. The weight of the cups was found to be 30.83 ± 0.016 g. The thickness, external diameter, internal diameter, and bottom diameter of the prepared cups were 3.01 ± 0.009 mm, 7.31 ± 0.004 cm, 6.74 ± 0.012 cm, and 4.71 ± 0.008 cm, respectively. The height and depth of the cups were 5.02 ± 0.012 cm and 4.50 ± 0.004 cm, respectively.

Figure 3. Developed biodegradable cups, front view and top view.

3.3.2. Colour, Hardness, Fracturability, and Water-Holding Capacity

The quality characteristics of the prepared cups were determined, and from Table 4 it was found that the predicted and actual values were close to each other, revealing that the fitted models were suitable for predicting the responses. Optimized cup samples were again analysed for colour values, hardness, and water-holding capacity, and the obtained results were measured in triplicate. The L*, a*, and b* values of the cup samples were 47.03 ± 0.021, 10.47 ± 0.041, and 24.77 ± 0.032, respectively. The L* value indicated that the prepared cups were darker in colour, which was due to the chemical changes that occurred with the polysaccharide constituents upon application of high temperature and pressure [29]. Redness tints with positive a* values were observed. A positive b* value indicates prepared cups with yellowish shades because corn cob, mango peel, and pineapple peel contain carotenoid pigments [31,32]. The hardness and fracturability of the cup sample was 2.411 ± 0.063 and 2.635 ± 0.033, respectively. The water-holding capacity of the cup was measured by filling it with 100 mL of water at a temperature of 100 °C. The WHC of the developed cup was 18.25 ± 0.026 min without any leakage. The obtained results for water-holding capacity were found to be in close agreement with those of Rana et al. [22].

3.3.3. FTIR Analysis

An FTIR analysis was performed to identify the functional groups present in the material. The FTIR spectra of the prepared biodegradable cups are shown in Figure 4. The generated peaks agreed with the known chemical compositions of corn cob, mango peel, and pineapple peel. The peak obtained at 3655.41 cm^{-1} corresponds to O-H stretching, and the presence of non-hydrogen-bonded hydroxyl groups corresponds to presences of cellulose [33–35]. The peak obtained at 2975.62 cm^{-1} indicates C-H stretching vibrations of the polysaccharide components with the presence of aldehydes [36]. The stretching vibration peak obtained in the range of 2900–3000 cm^{-1} related to the aliphatic hydrocarbons that may be the part of acid and other organic compounds present in the fruit peels [9]. The peak at 1383.68 cm^{-1} corresponds to the methyl group vibrations with C-H stretching. The carboxylic groups identified at 1254.47 cm^{-1}, indicating C-O stretching, correspond to the presence of hemicellulose [37]. The O–H and C–O groups play an important role for providing cross-linking networks and compatibility with starch-based or synthetic matrices in such biocomposites [38]. The presence of carboxylic groups also identifies pectin, as it contains galacturonic acid. C-O-C stretching identified at 1150.33 cm^{-1} corresponds to the glycosidic linkages involved in cellulose, hemicellulose, lignin, pectin, and starch [39]. The peak identified in the fingerprint region at 1070.3 cm^{-1} is due to C-O bonding from the polysaccharides. Peaks in the range of 500–600 $cm-^{1}$ indicate bending vibration with C-O-H bonding. This study demonstrated the essential correlation between the functional groups O-H, C-H, C=O, C-O-C, and C-O in the developed cup sample. It was revealed that biodegradable cups prepared from corn cob, mango peel, pineapple peel, and binder showed the presence of cellulose, hemicellulose, lignin, and pectin components, which underlines structural integrity, binding properties, water resistance, and biodegradability of the end product, confirming their relevance to material selection. The obtained FTIR results were in close agreement with the biodegradable cups prepared from a combination of paddy straw and pine needles by Gupta et al. [24].

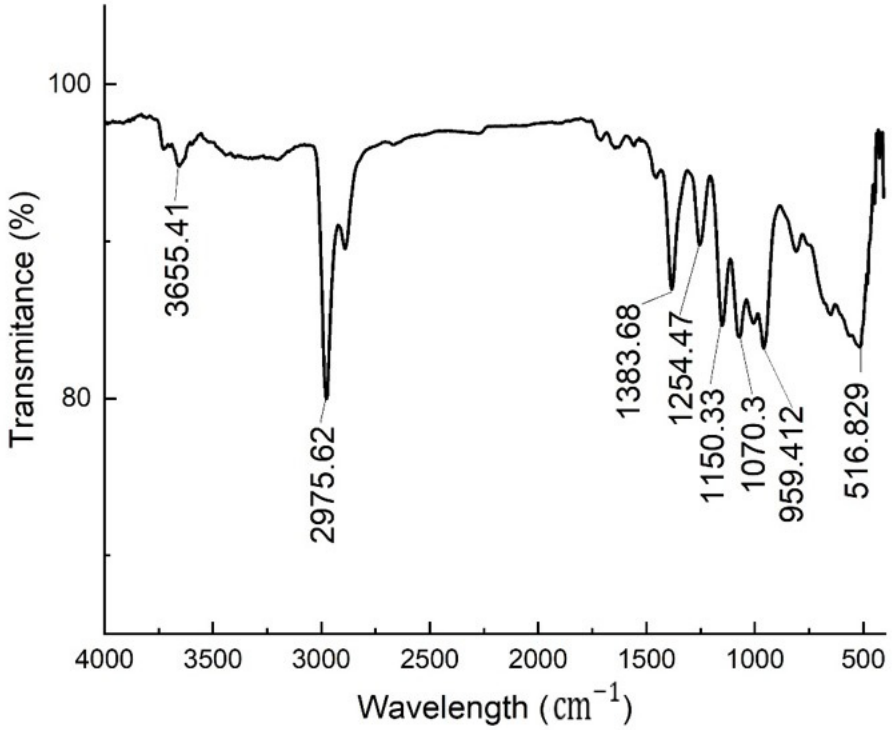


Figure 4. FTIR spectra of the prepared cup sample.

3.3.4. X-Ray Diffraction (XRD)

Crystallinity plays a critical role in enhancing the textural and thermal stability of composites formulated from diverse fibre-based natural materials from agriculture waste. Structural composition insights for the biodegradable cup, examined via X-ray diffraction (XRD) analysis, are presented in Figure 5. The XRD spectrum of the prepared cup indicates distinct diffraction peaks at 2θ values of 14.73, 16.05, 19.12, 22.32, 22.98, 24.19, 26.84, 28.41, 29.91, 35.29, 36.13, and 40.78 degrees, which collectively signify the crystalline domains within the sample [9]. A pronounced high-intensity peak at around 22° is characteristic of crystalline cellulose, specifically corresponding to the lattice planes observed in cellulose I structures [40]. The crystallinity index of the prepared biodegradable cup sample was 44.4%. Broad, less intense features within the 16–18° range are attributed to amorphous content, primarily resulting from hemicellulose, lignin, disordered cellulose, and pectin regions [41]. These findings substantiate that the biodegradable cup possesses a semicrystalline structure, a typical feature of many natural-fibre-based composites [42]. The semi-crystalline nature can be ascribed to the coexistence of both amorphous and crystalline phases within the matrix. Observed spectral irregularities likely arise from the ingredient composition, the fibre matrix, and intermolecular interactions [24]. The utilization of corn and fruit processing waste, combined with starch as a binder and processed through compression moulding, enhances structural compactness and promotes favourable crystallinity. This, in turn, significantly improves the product's functional performance for practical applications. Similar structural characteristics have been reported for other plant-derived biodegradable materials in studies carried out by Purghorbani et al. [9], Gupta et al. [24], and Warrier et al. [40].

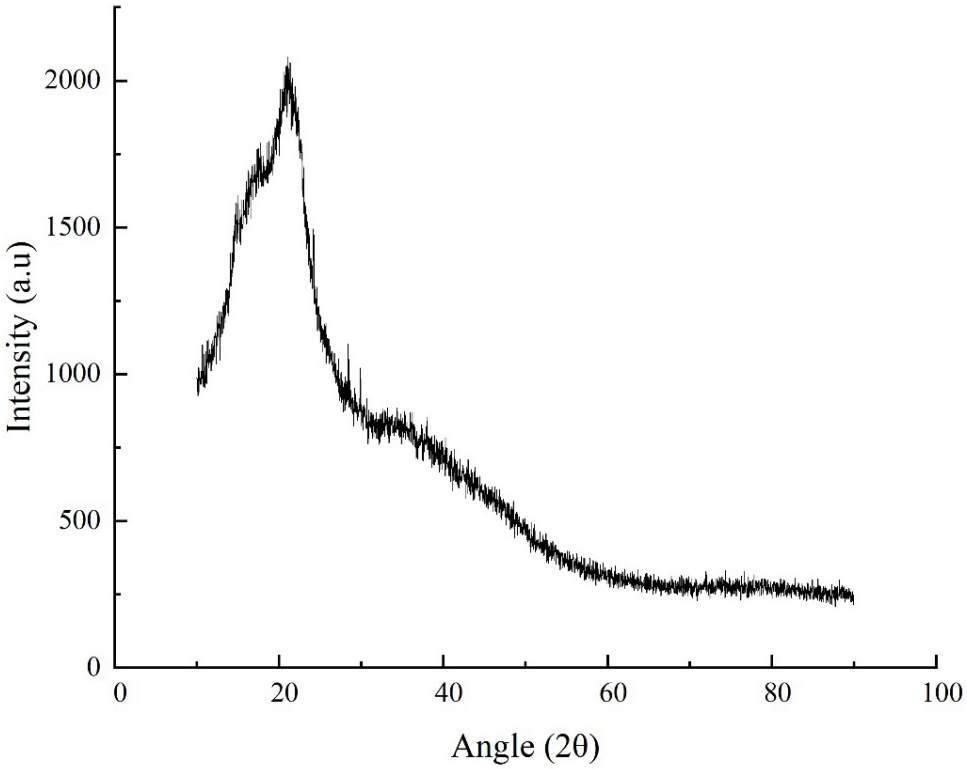


Figure 5. XRD of biodegradable cup sample.

3.3.5. Scanning Electron Microscopy

The surface morphology of the cup sample was observed using scanning electron microscopy at 1000× magnification, as shown in Figure 6. From the obtained micrographs, a cellulose- and hemicellulose-reinforced nature with uneven surfaces with some pores and several projections were identified. This may be due to different material combinations, particle sizes, heterogeneous fibre distributions, and alignment of cellulose fibres in different directions [40]. The cup sample shows the compact nature, which can be attributed to natural composition of cellulose and pectin present in fruit peels and corn cob, which forms a cohesive structure [9]. Purghorbani et al. [9] reported similar structural results for the biodegradable cups prepared from watermelon peel waste. A well-packed arrangement and reinforcing nature ensured better textural characteristics and WHC because of the fibrous network and compression mechanism. Warrier et al. [40] reported a similar structural matrix for biodegradable carry-bags.

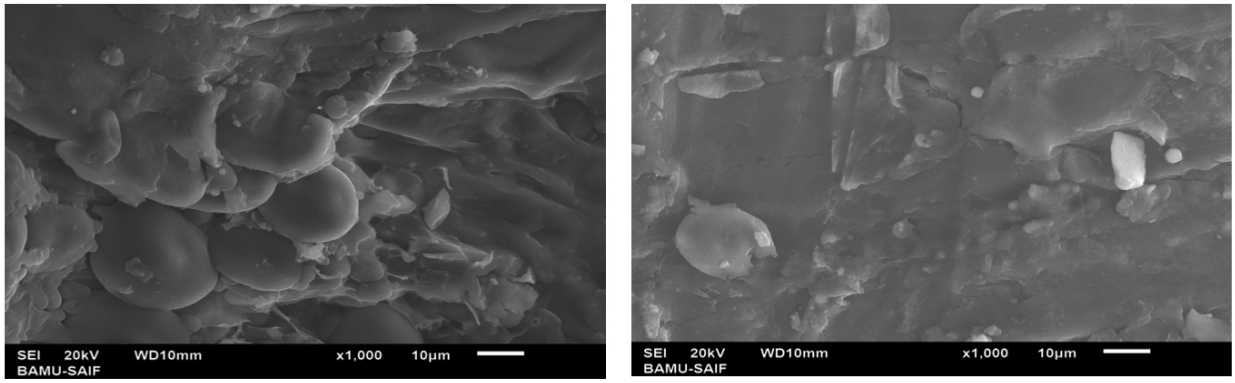


Figure 6. SEM micrographs of prepared cup sample.

3.3.6. Biodegradability by Soil Burial Test

The biodegradation of cup samples was studied using a soil burial test. The sample was kept for 30 days of study with 5-day-interval changes observed after removal from the soil. The changes observed during biodegradation and percentage degradation rate of the cup sample is presented graphically in Figure 7. The biodegradation rate mainly depends upon the soil moisture content and the chemical composition of the material, as optimal soil moisture easily facilitates hydrolysis at glycosidic bonds with the presence of soil microbial flora [9]. The figure shows that on Day 15, microbial action occurred in the samples, after which faster degradation was observed. Changes in weight loss during degradation occur owing to the action of microorganisms, enzymes, oxygen, and humid conditions [43]. The percentage degradation was calculated based on weight loss. More than 50% degradation was observed on Day 15. Complete degradation of the cup sample was achieved within 30 days. A similar biodegradation behaviour was also reported by Harikrishnan et al. [44].

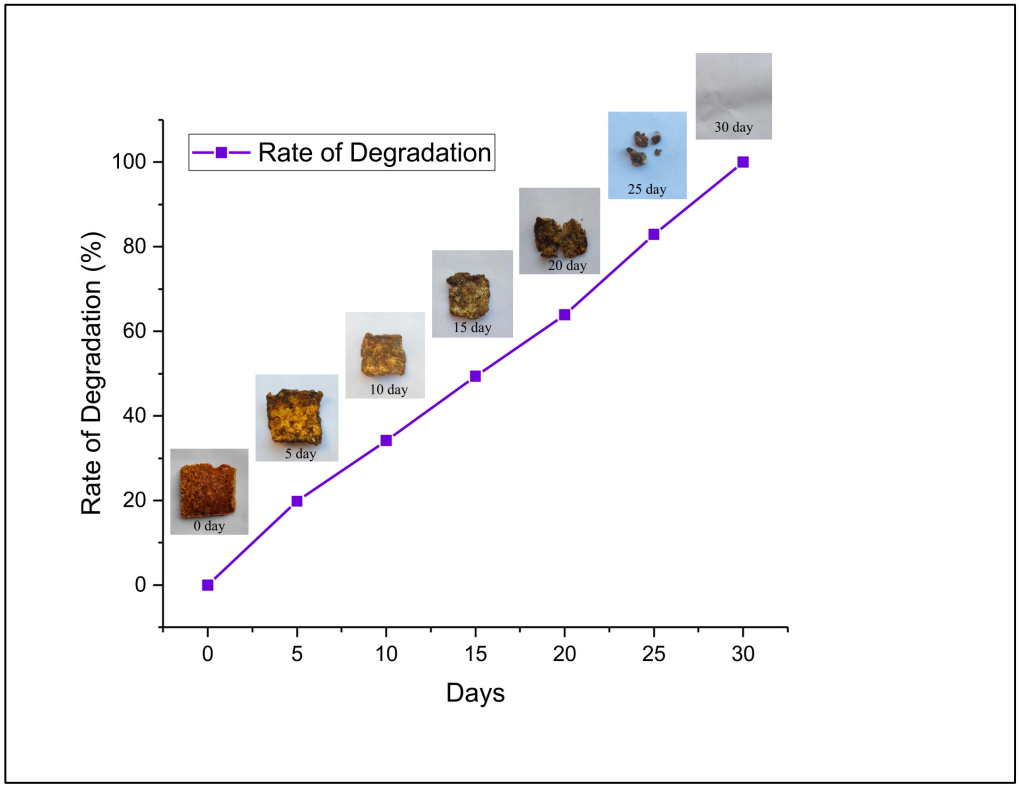


Figure 7. Biodegradability study of cup sample.

4. Conclusions

This study investigated the potential of utilizing corn and fruit processing waste to develop biodegradable cups. Ingredient levels were optimized using response surface methodology (Box–Behnken design). Cups prepared with corn cob (34 g), mango peel (40 g), and pineapple peel (26 g) exhibited a hardness of 2.41 ± 0.063 kg, an L* value of 47.03 ± 0.021, and a water-holding capacity of 18.25 ± 0.026 min. The prepared biodegradable cups exhibited good colour, functional, and textural properties. The FTIR analysis revealed that the samples contained polysaccharide constituents in the presence of cellulose, hemicellulose, lignin, and pectin. XRD study revealed semicrystalline nature with a crystallinity index of 44.4%. SEM analysis showed good surface morphology with a crosslinking network of fibres. The prepared biodegradable cups degraded into soil within 30 days. The prepared cups will serve as an alternative to

single-use plastic items for serving tea, coffee, and soup, thereby helping to mitigate adverse impacts on ecosystems.

Limitations and future implications: Competition for material availability, variability in raw material uniformity, processing complexity, and cost are the primary limitations identified in this research study. This research lays the groundwork for further exploration of byproducts and natural biomass in the development of biodegradable cups and for optimizing processing parameters such as time, temperature, and pressure. Future studies should also investigate the long-term performance of these cups with both cold and hot food products. Further research directions should focus on economic feasibility, mechanical properties, environmental impact assessment of these biodegradable cups in real-world applications, and comprehensive evaluation of their biodegradability through life cycle assessment.

Author Contributions: Writing the original draft and formal analysis, S.S.W.; supervision and conceptualization, R.B.K.; visualization, S.K.S.; writing, analysis, and design, R.A.G.; methodology and resources, V.G.; review and editing, A.M.S.; supervision, resources, and funding acquisition, K.B. All authors have read and agreed to the published version of the manuscript.

Funding: The Funding is supported by the University of Debrecen Program for Scientific Publication.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Acknowledgments: The authors would like to convey thanks and express their gratitude to the University of Debrecen for collaborating in this project. The first author would like to express his sincere gratitude to CIVITA Food, Ltd., Hungary, for providing the facility to conduct experimental work and trials and Author Ayaz Mukarram Shaikh also would like to Acknowledge "This article/publication is based upon work from COST Action FoodWaStop, CA22134, supported by COST (European Cooperation in Science and Technology)."

Conflicts of Interest: Author Vaszko Gabor is employed by the company CIVITA GROUP Plc. Sangram S. Wandhekar declare that this study received facility to conduct experimental work and trials as support from CIVITA Food, Ltd. The company was not involved in the study design, collection, analysis, interpretation of data, the writing of this article or the decision to submit it for publication.

Abbreviations

RSM	Response surface methodology
BBD	Box–Behnken design
WHC	Water-holding capacity
ANOVA	Analysis of variance
CC	Corn cob
MP	Mango peel
PP	Pineapple peel
FTIR	Fourier transfer infrared spectroscopy
SEM	Scanning electron microscopy
XRD	X-ray diffraction

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