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Balancing Mechanical Properties, Water Resistance and Soil Degradability of Rice Flour/CMC-Based Biodegradable Drinking Straws

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Abstract

The development of biodegradable drinking straws requires a balance between mechanical integrity, flexibility, water resistance, and post-use degradability. This study investigated the effects of rice flour-to-carboxymethyl cellulose (CMC) ratio and plasticizer conditions on the functional performance of biodegradable drinking straws. Five rice flour:CMC ratios (1:3, 1.5:2.5, 2:2, 2.5:1.5, and 3:1) were combined with two plasticizers (glycerol and sorbitol) at three loadings (1.5, 2.0, and 3.0 mL), resulting in 30 formulations. The resulting straws were evaluated for tensile strength, elongation at break, water resistance, and soil-burial degradation. Tensile strength ranged from 0.588 to 3.822 MPa, with the highest value obtained at a rice flour : CMC ratio of 1:3 containing 1.5 mL sorbitol. Elongation at break ranged from 12.545 to 88.964%, with the maximum achieved at a ratio of 3:1 containing 2.0 mL glycerol, demonstrating a clear strength–flexibility trade-off. Water resistance varied from 25 to 74%, while soil-burial mass loss reached 86.2–100% after 21 days. The different formulations maximizing tensile strength, flexibility, and water resistance indicate that plasticizer performance is strongly dependent on matrix composition rather than plasticizer identity alone.

Keywords: *biodegradable drinking straw; rice flour; carboxymethyl cellulose; water resistance; soil-burial degradation*

Abstrak

Pengembangan sedotan minuman yang dapat terurai secara hayati (*biodegradable*) memerlukan keseimbangan antara integritas mekanis, fleksibilitas, ketahanan terhadap air, dan kemampuan terurai setelah penggunaan. Penelitian ini mengkaji pengaruh rasio tepung beras terhadap *carboxymethyl cellulose* (CMC) dan kondisi *plasticizer* terhadap kinerja fungsional sedotan tersebut. Lima rasio tepung beras : CMC (1:3, 1,5:2,5, 2:2, 2,5:1,5, dan 3:1) dikombinasikan dengan dua jenis *plasticizer* (gliserol dan sorbitol) pada tiga tingkat takaran (1,5; 2,0; dan 3,0 mL), sehingga menghasilkan 30 formulasi. Sedotan yang dihasilkan dievaluasi berdasarkan kekuatan tarik, elongasi saat putus, ketahanan terhadap air, dan degradasi melalui metode penguburan dalam tanah. Kekuatan tarik berkisar antara 0,588 hingga 3,822 MPa, dengan nilai tertinggi diperoleh pada rasio tepung beras : CMC 1:3 yang mengandung 1,5 mL sorbitol. Elongasi saat putus berkisar antara 12,545 hingga 88,964%, dengan nilai maksimum dicapai pada rasio 3:1 yang mengandung 2,0 mL gliserol, yang menunjukkan adanya *trade-off* (pertukaran nilai) yang jelas antara kekuatan dan fleksibilitas. Ketahanan terhadap air bervariasi antara 25 hingga 74%, sedangkan penurunan massa akibat penguburan dalam tanah mencapai 86,2–100% setelah 21 hari. Fakta bahwa formulasi berbeda menghasilkan nilai maksimum untuk kekuatan tarik, fleksibilitas, dan ketahanan air secara terpisah menunjukkan bahwa kinerja *plasticizer* sangat bergantung pada komposisi matriks, bukan sekadar jenis *plasticizer* itu sendiri.

Kata kunci: *sedotan minuman biodegradable; tepung beras; carboxymethyl cellulose; ketahanan terhadap air; degradasi penguburan dalam tanah*

1. Introduction

The extensive use of petroleum-based single-use plastics has generated increasing environmental concern because of their persistence and accumulation in terrestrial and aquatic ecosystems. Drinking straws represent a relatively small fraction of total plastic consumption; nevertheless, their short service life, widespread use, and limited recovery after disposal make them a relevant target for replacement with biodegradable alternatives [1], [2], [3]. This has encouraged the development of drinking straws derived from renewable biopolymers, including starch, cellulose derivatives, chitosan, and other polysaccharide-based materials. Among these materials, starch is particularly attractive because of its abundance, low cost, renewability, and inherent biodegradability. However, starch-based materials generally exhibit high hydrophilicity and limited mechanical stability, which can restrict their performance in applications involving direct and prolonged contact with aqueous beverages [4], [5], [6], [7].

Rice-derived materials offer considerable potential as a renewable polysaccharide source for biodegradable products. Rice flour contains a high proportion of starch and can form a continuous matrix following gelatinization, making it suitable for the fabrication of biodegradable structures. Nevertheless, a rice-flour-dominant matrix alone may exhibit brittleness, dimensional instability, and sensitivity to water. These limitations are particularly important for drinking-straw applications because, unlike conventional thin films, straws must maintain a three-dimensional tubular structure, withstand mechanical handling, and resist softening during contact with liquids while remaining biodegradable after disposal. Consequently, formulation strategies developed for biodegradable films cannot necessarily be transferred directly to drinking straws without considering these additional functional requirements.

Blending starch-rich materials with carboxymethyl cellulose (CMC) represents one approach to improving the properties of polysaccharide-based materials. CMC is a water-soluble cellulose derivative containing hydroxyl and carboxymethyl functionalities and is widely used to modify the film-forming and mechanical characteristics of biopolymer matrices. Previous studies on starch/CMC and related polysaccharide composites have demonstrated that variations in polymer composition can substantially influence tensile strength, flexibility, and water-related behavior [8], [9], [10], [11]. Chitosan has also been incorporated into starch- and CMC-based matrices because of its film-forming characteristics and compatibility with polysaccharide systems. In the present formulation, nano-SiO_2 was additionally incorporated as a fixed reinforcing component. However, because the chitosan and nano-SiO_2 contents were maintained constant, the principal formulation variables investigated in this study were the rice flour-to-CMC ratio and plasticizer conditions.

Plasticization is particularly important in starch- and cellulose-based materials because strong intermolecular association among polysaccharide chains can result in brittle structures. Polyol plasticizers such as glycerol and sorbitol are commonly used to increase chain mobility and improve material flexibility. Their effects, however, are not necessarily equivalent. Glycerol and sorbitol differ in molecular size, hydroxyl functionality, hygroscopic behavior, and their interactions with surrounding polymer chains [12], [13], [14], [15]. Consequently, changing the type and amount of plasticizer may simultaneously influence mechanical strength, elongation, and water-related properties. An increase in flexibility, for example, may be accompanied by reduced tensile resistance or increased sensitivity to water. Thus, the selection of a plasticizer cannot be based solely on maximizing a single material property.

Recent studies have demonstrated the feasibility of producing biodegradable straws and related food-contact materials from starch-based matrices combined with CMC, gelatin, chitosan, or other biopolymers. For example, the development of sorghum flour-based edible straws containing gelatin and different CMC concentrations has demonstrated the importance of matrix composition in controlling the functional properties of tubular biopolymer products. Studies on biodegradable starch/CMC films and carboxymethylated cellulose-based composites have similarly shown that formulation strongly influences mechanical and water-related properties. Nevertheless, much of the available literature has focused on either flat biodegradable films or a limited number of straw formulations, while systematic assessment of the combined effects of polymer ratio, plasticizer type, and plasticizer loading across a broad formulation range remains relatively limited [3], [5], [16], [17], [18], [19].

An additional challenge is that the performance of biodegradable drinking straws is inherently multi-objective. High tensile strength alone does not necessarily indicate an optimal straw if the material is excessively brittle, while very high flexibility may compromise structural rigidity. Similarly, improved resistance to water during use must be balanced against the ability of the material to degrade after disposal. Mechanical performance, aqueous durability, and biodegradability should therefore be considered simultaneously rather than as independent optimization targets. This balance is particularly relevant for single-use biodegradable products, which require sufficient in-use durability over a relatively short service period but should retain substantial post-use degradability.

Despite increasing interest in biodegradable straws, the interactive effects of rice flour/CMC composition and glycerol–sorbitol plasticization on these competing functional requirements remain insufficiently understood. In particular, direct comparison across a systematic formulation space is needed to establish whether the plasticizer providing the greatest flexibility also provides favorable tensile strength and water resistance, and whether improvements in short-term functionality compromise subsequent degradation. Addressing these questions is important for moving formulation development beyond the conventional selection of a material based solely on its highest individual property value.

Therefore, this study systematically investigated the effects of five rice flour:CMC ratios (1:3, 1.5:2.5, 2:2, 2.5:1.5, and 3:1), two plasticizer types (glycerol and sorbitol), and three plasticizer loadings (1.5, 2.0, and 3.0 mL), resulting in 30 different straw formulations. The functional performance of the resulting biodegradable straws was evaluated in terms of tensile strength, elongation at break, water resistance, and soil-burial degradation. Rather than identifying an optimum formulation based on a single maximum response, particular emphasis was placed on evaluating the trade-offs among mechanical resistance, flexibility, short-term water resistance, and post-use degradability. This multi-response formulation approach is intended to provide a practical basis for selecting balanced rice flour/CMC-based formulations for biodegradable drinking-straw applications.

2. Materials and Methods

2.1. Materials

Rice flour and carboxymethyl cellulose (CMC) were used as the principal polysaccharide components for the preparation of biodegradable drinking straws. Chitosan was incorporated as a supporting biopolymer, while nano-SiO_2 was used as an inorganic reinforcing component. Glycerol and sorbitol were employed separately as plasticizers. Acetic acid was used for the preparation of the chitosan solution, while distilled water was used as the dispersion medium and for rice-flour gelatinization. A chitosan solution was prepared using 2 g of chitosan per 100 mL of 1% (v/v) acetic acid solution, while the nano-SiO_2 dispersion contained 0.16 g of nano-SiO_2 per 100 mL of distilled water.

2.2. Experimental Design and Formulations

A systematic formulation design was employed to investigate the effects of the rice flour-to-CMC ratio, plasticizer type, and plasticizer loading on the functional properties of the biodegradable straws. Five rice flour : CMC mass ratios were investigated: 1:3, 1.5:2.5, 2:2, 2.5:1.5, and 3:1. Two plasticizers, glycerol and sorbitol, were independently incorporated at volumes of 1.5, 2.0, and 3.0 mL. The combination of five rice flour : CMC ratios, two plasticizer types, and three plasticizer loadings resulted in a total of 30 formulations. Chitosan and nano-SiO_2 contents were maintained constant throughout the experiment so that the effects of the principal formulation variables could be comparatively evaluated.

Table 1. Experimental variables used for biodegradable straw formulation

Formulation factor	Experimental levels
Rice flour : CMC ratio	1:3; 1.5:2.5; 2:2; 2.5:1.5; 3:1
Plasticizer type	Glycerol; Sorbitol
Plasticizer loading	1.5; 2.0; 3.0 mL
Chitosan	Fixed
Nano-SiO_2	Fixed
Total formulations	30

2.3. Preparation of Rice Flour/CMC-Based Biodegradable Straws

The biodegradable straws were prepared through sequential dispersion, gelatinization, blending, plasticization, casting, and tubular shaping. First, 2 g of chitosan was dissolved in 100 mL of 1% (v/v) acetic acid solution and stirred at 70 °C for 20 min until a homogeneous solution was obtained. Separately, 0.16 g of nano-SiO_2 was dispersed in 100 mL of distilled water and stirred at 70 °C for 10 min. Rice flour was subsequently added according to the predetermined rice flour : CMC formulation and continuously stirred at 70 °C for 10 min to promote gelatinization and formation of a homogeneous paste. The gelatinized rice-flour/nano-SiO_2 mixture was then combined with the previously prepared chitosan solution and stirred at 70 °C for 15 min. CMC was subsequently incorporated according to the specified rice flour : CMC ratio, followed by further stirring at 70 °C for 15 min.

Either glycerol or sorbitol was then added at 1.5, 2.0, or 3.0 mL, depending on the formulation. The mixture was continuously stirred at 70 °C for an additional 30 min to facilitate uniform plasticizer distribution throughout the composite matrix. A 70-mL aliquot of the resulting mixture was poured into a mold and dried at room temperature for 2 days. The dried material was subsequently shaped into a tubular straw structure and further dried in an oven at 100 °C for 2 h. The resulting straws were cut to a uniform length of 16 cm before functional testing.

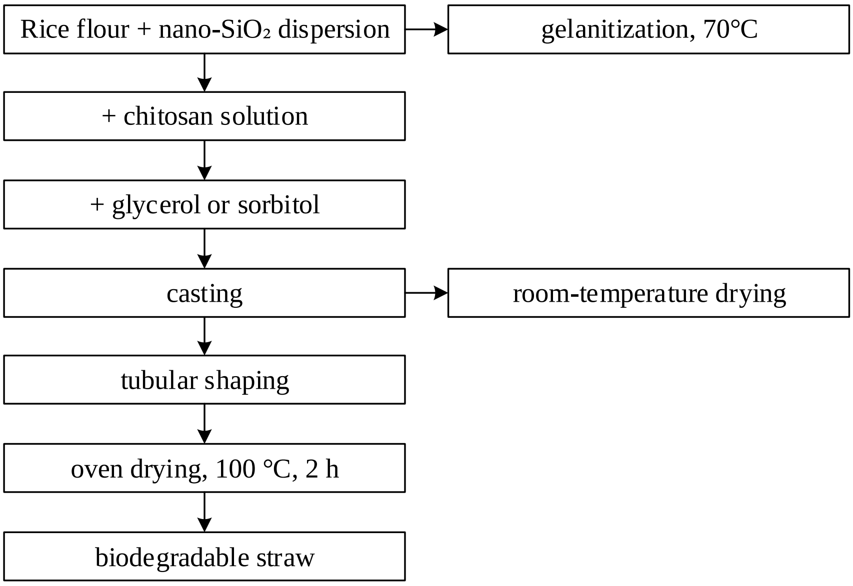

Figure 1: Experimental procedure

2.4. Tensile Strength and Elongation at Break

The mechanical performance of the biodegradable straws was evaluated in terms of tensile strength (TS) and elongation at break (EAB) using a Universal Testing Machine (UTM). The specimens used for tensile testing had an initial length of approximately 5.5 cm, a width of 2 cm, and a thickness of approximately 0.1 cm, corresponding to an initial cross-sectional area of approximately 2×10^{-5} m². Tensile strength was calculated from the maximum load sustained by the specimen before failure relative to its initial cross-sectional area:

$$TS = \frac{Fmax}{A}$$

where TS is the tensile strength (Pa or MPa), F_{max} is the maximum force at break (N), and is the initial cross-sectional area of the specimen (m²). Elongation at break was determined from the increase in specimen length at failure relative to its initial length:

$$EAB(\%) = \frac{(Lf - Lo)}{Lo \times 100}$$

where Lo is the initial gauge length and is the specimen length at break.

2.5. Water Resistance

Water resistance was evaluated to determine the ability of the biodegradable straw material to resist water uptake during aqueous exposure. Specimens with an initial dry mass of approximately 1 g were exposed to water under the experimental conditions used in this study. After immersion, excess surface water was removed and the specimens were reweighed. Water absorption was determined from the increase in specimen mass relative to the initial dry mass:

$$WA\ (\%) = \frac{Wt - Wo}{Wo} \times 100$$

where *Wo* is the initial dry mass and *Wt* is the specimen mass after water exposure. Water resistance was subsequently expressed relative to the measured water absorption according to the calculation procedure applied in the experimental dataset.

2.6. Soil-Burial Degradation

The post-use degradability of the biodegradable straws was evaluated using a soil-burial test. Specimens with known initial dry masses were buried in soil under the experimental conditions and recovered periodically during the test period. After recovery, adhering soil was carefully removed, and the specimens were dried and weighed. The percentage mass loss was calculated as:

$$Mass\ loss\ (\%) = \frac{Wo - Wt}{Wo} \times 100$$

where Wo is the initial dry mass of the specimen and Wt is the residual dry mass after burial time. The degradation behavior was evaluated for up to 21 days, and the resulting gravimetric mass loss was used to compare the post-use degradation behavior among the different formulations.

3. Results and Discussion

3.1. Mechanical Properties

Mechanical performance is a fundamental requirement for biodegradable drinking straws because the material must maintain sufficient structural integrity during handling while retaining adequate flexibility to avoid brittle failure [20], [21]. In the present study, tensile strength (TS) and elongation at break (EAB) varied considerably across the 30 formulations, demonstrating that the mechanical response was influenced by the rice flour : CMC ratio, plasticizer type, and plasticizer loading.

The tensile strength values ranged from 0.588 to 3.822 MPa. The highest tensile strength of 3.822 MPa was obtained for the formulation containing a rice flour : CMC ratio of 1:3 with 1.5 mL sorbitol. In contrast, the lowest tensile strength of 0.588 MPa was observed for the formulation with a rice flour : CMC ratio of 2:2 containing glycerol, at plasticizer loadings of both 2 and 3 mL. These results indicate that tensile strength did not change monotonically with either polymer ratio or plasticizer loading. Therefore, increasing the proportion of either rice flour or CMC alone cannot fully explain the mechanical response.

The relatively high tensile strength observed in the CMC-rich formulation may be associated with improved cohesive interactions within the polysaccharide matrix [22]. CMC contains numerous hydroxyl and carboxymethyl functionalities capable of interacting with starch-rich components and chitosan. Such interactions have been reported to promote matrix cohesion and influence stress transfer in starch/CMC and related polysaccharide composites [23]. However, the present data also demonstrate that the effect of CMC was dependent on plasticizer conditions, suggesting that polymer composition and plasticization should be considered simultaneously rather than independently [24].

Plasticizer loading further produced a formulation-dependent response. Polyol plasticizers generally increase molecular mobility by reducing intermolecular association among adjacent polymer chains . At an appropriate concentration, this effect can reduce brittleness and facilitate deformation. Excessive plasticization, however, may weaken cohesive interactions and decrease resistance to applied stress. The non-linear tensile-strength response observed in the present formulations is therefore consistent with competition between matrix cohesion and plasticizer-induced chain mobility. Because molecular interactions were not directly characterized in Paper 1, this explanation should be regarded as a plausible interpretation based on the established behavior of polysaccharide–polyol systems rather than direct mechanistic evidence from the present experiment [6], [25].

Elongation at break showed an even broader formulation-dependent variation, ranging from 12.545 to 88.964%. The highest EAB of 88.964% was obtained for the rice flour : CMC ratio of 3:1 containing 2 mL glycerol, whereas the lowest value of 12.545% was observed for the 1:3 formulation containing 3 mL glycerol. For sorbitol-plasticized formulations, elongation ranged approximately from 20.909 to 81.691%. These results confirm that substantial changes in flexibility can be achieved by modifying both matrix composition and plasticization conditions.

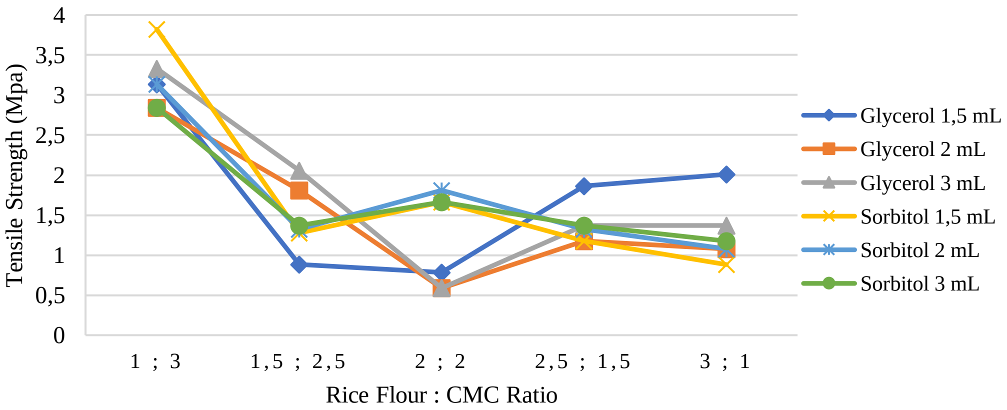

Figure 2a. Tensile strength as a function of rice flour : CMC ratio for glycerol- and sorbitol-plasticized straws

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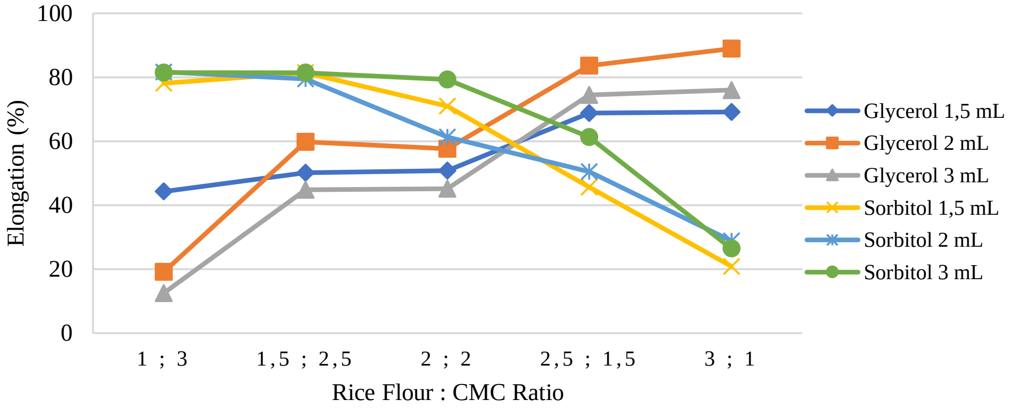

Figure 2b. Elongation at break as a function of rice flour : CMC ratio for glycerol- and sorbitol-plasticized straws

A particularly interesting observation was the contrasting response of glycerol- and sorbitol-plasticized formulations to changes in rice flour : CMC composition. In the glycerol series, elongation generally increased as the formulation became richer in rice flour. Sorbitol-containing formulations showed a different compositional response, with relatively high elongation also occurring in CMC-rich matrices. This result indicates that the effectiveness of a plasticizer cannot be separated from the composition of the surrounding polymer matrix. In other words, plasticizer performance was matrix-dependent.

This behavior can reasonably be related to differences in the molecular characteristics of glycerol and sorbitol. Both are hydroxyl-rich polyols, but they differ in molecular size and hydroxyl functionality, which can affect their distribution and interactions within a polysaccharide matrix [6]. Glycerol is smaller and can promote chain mobility efficiently, whereas sorbitol has a larger molecular structure and may interact differently with polymer chains [9], [26]. Nevertheless, the present results do not support describing either plasticizer as universally superior because their effects varied with the rice flour : CMC ratio and loading.

Most importantly, the formulation exhibiting the maximum tensile strength was not the formulation exhibiting maximum elongation. The highest TS occurred at rice flour: CMC 1:3 with 1.5 mL sorbitol, whereas the highest EAB occurred at 3:1 with 2 mL glycerol. This divergence demonstrates a clear strength–flexibility trade-off. Maximizing cohesive resistance to tensile loading and maximizing deformation capability therefore represent different formulation objectives.

Accordingly, mechanical optimization of biodegradable drinking straws should not rely solely on the highest tensile-strength value. A straw requires sufficient strength to retain its tubular integrity during handling but also sufficient flexibility to tolerate deformation without brittle fracture. The present results demonstrate that these two requirements can be adjusted through the combined selection of rice flour : CMC ratio and plasticizer conditions.

3.2. Water Resistance

Water resistance is particularly important for biodegradable drinking straws because direct contact with aqueous beverages can promote water penetration, swelling, softening, and eventual loss of structural integrity [20], [27]. Across the investigated formulations, water resistance varied from approximately 25 to 74%, indicating that the resistance of the straw matrix to water exposure was strongly dependent on formulation conditions.

The highest water-resistance value of 74% was recorded for two different experimental conditions, namely sample 10 containing 2 mL glycerol and sample 20 containing 1.5 mL sorbitol. Conversely, the lowest value of approximately 25% was obtained for sample 11 containing 3 mL glycerol. The occurrence of the same maximum response under different plasticizer conditions provides further evidence that water resistance was not controlled exclusively by plasticizer identity.

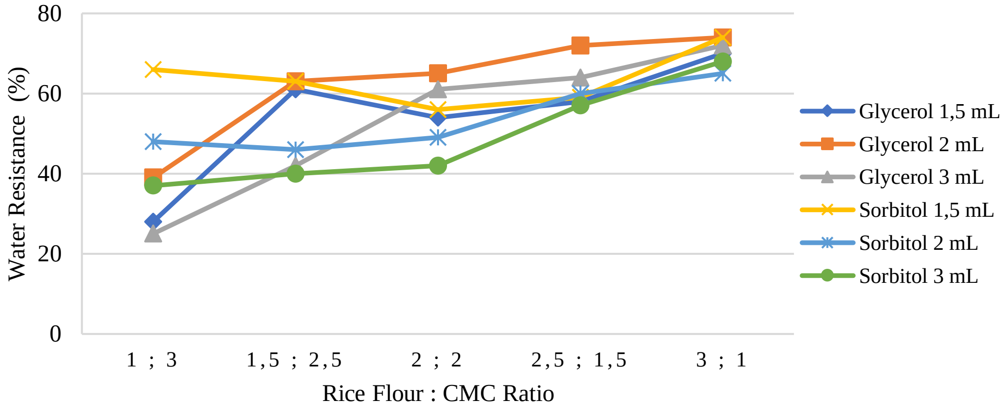

Figure 3. Water resistances

More importantly, increasing plasticizer loading did not consistently improve water resistance. In some formulations, increasing the amount of plasticizer improved resistance to aqueous exposure, whereas in others the opposite behavior was observed. Such non-monotonic responses are reasonable for hydrophilic multicomponent systems because plasticizers can simultaneously modify polymer-chain mobility, matrix compactness, and accessibility of hydrophilic groups to water [28], [29]. Both glycerol and sorbitol contain multiple hydroxyl groups and are therefore capable of interacting with water as well as with the surrounding polysaccharide matrix [30]. Consequently, the effect of plasticization on water resistance represents a balance between changes in matrix organization and the hydrophilic character introduced by the polyol. Excessive plasticization may increase free volume or molecular mobility and facilitate water penetration, whereas an appropriately formulated matrix may retain greater physical integrity during short-term aqueous exposure [9], [28].

The present results therefore demonstrate that neither glycerol nor sorbitol can be regarded as universally superior for improving water resistance. Instead, the effect of each plasticizer depended on its loading and the composition of the surrounding rice flour/CMC matrix. This finding is consistent with the mechanical results, in which plasticizer performance was likewise strongly formulation-dependent.

It should be emphasized that the measured water-resistance values represent the response under the immersion conditions used in this study. They should not be interpreted as direct evidence of surface hydrophobicity or as a prediction of commercial soaking lifetime without corresponding contact-angle or prolonged immersion measurements. Nevertheless, the maximum value of 74% demonstrates that appropriate formulation can substantially improve resistance to short-term water exposure relative to less favorable formulations within the same material system.

3.3. Soil-Burial Degradation Behavior

The environmental advantage of a biodegradable drinking straw depends not only on its functionality during use but also on its ability to undergo degradation after disposal. The developed rice flour/CMC-based straws exhibited extensive mass loss during soil burial, with values ranging from approximately 86.2 to 100% after 21 days, indicating high susceptibility of the composite matrices to deterioration under the investigated soil conditions.

A clearer compositional tendency was observed for soil-burial degradation than for mechanical properties or water resistance. In general, formulations with higher proportions of rice flour exhibited greater mass loss [14], [15]. For example, at a glycerol loading of 1.5 mL, soil-burial mass loss increased from approximately 86.2% for the rice flour : CMC ratio of 1:3 to 98.8% for the 3:1 formulation. Several formulations ultimately exhibited complete gravimetric mass loss during the experimental period.

The increased degradation observed in rice-flour-rich formulations may be associated with the greater proportion of readily degradable carbohydrate components accessible to water and soil microorganisms [14], [15]. Starch-rich domains can undergo hydration and biological deterioration under moist soil conditions, progressively weakening the composite structure. CMC, chitosan, and plasticizer content may additionally influence water penetration and accessibility of the polymer matrix, resulting in formulation-dependent degradation rates [3], [10], [15].

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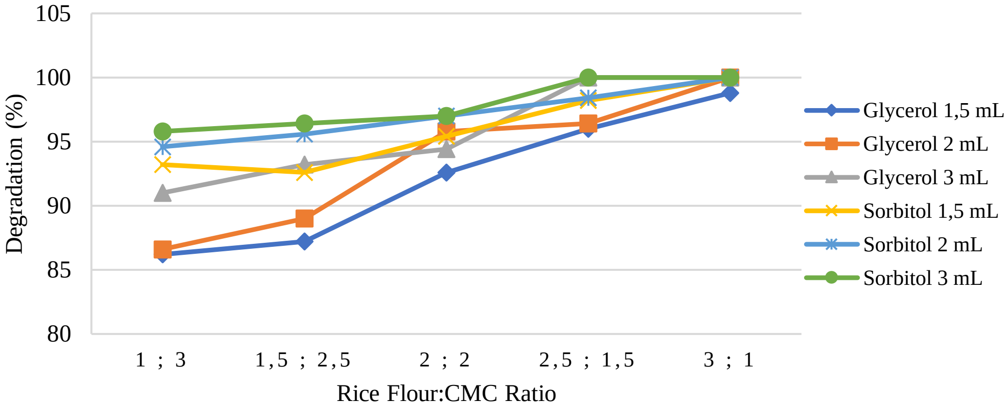

Figure 4. Soil-burial mass loss/degradation

Differences were also observed between glycerol- and sorbitol-containing formulations. The glycerol series exhibited soil-burial mass loss ranging approximately from 86.2 to 100%, whereas the sorbitol series ranged approximately from 92.6 to 100%. However, these ranges should not be interpreted as evidence that sorbitol intrinsically produces greater biodegradability because matrix composition and plasticizer loading varied simultaneously across the formulation space [6], [8], [9].

An important outcome is that relatively high water resistance or mechanical performance did not prevent substantial degradation after disposal. All formulations retained extensive soil-burial mass loss after 21 days. This finding indicates that improving short-term functional properties did not eliminate the susceptibility of the polysaccharide-based matrices to post-use deterioration.

The present soil-burial results should nevertheless be distinguished from standardized compostability measurements. Gravimetric mass loss during soil burial reflects physical and biological deterioration of the specimens but does not directly quantify mineralization of organic carbon to CO_2. Accordingly, the values reported here demonstrate rapid soil-burial degradation under the investigated conditions, rather than certified industrial compostability [18], [20], [27].

3.4. Overall Functional Performance and Formulation Trade-Offs

This section is, in my view, the key integrative component of Paper 1. The combined results demonstrate that the functional performance of the biodegradable straws cannot be adequately represented by a single response parameter. Instead, formulation changes produced different and sometimes competing effects on tensile resistance, flexibility, water resistance, and soil-burial degradation.

Table 2. Overall functional performance of the developed rice flour/CMC-based biodegradable straws

Functional property	Experimental range	Maximum observed response	Functional significance
Tensile strength	0.588–3.822 MPa	3.822 MPa	Resistance to mechanical loading
Elongation at break	12.545–88.964%	88.964%	Flexibility and deformation capability
Water resistance	25–74%	74%	Resistance to short-term aqueous exposure
Soil-burial mass loss	86.2–100% after 21 d	100%	Post-use degradation potential

The most important observation is that the maximum responses were not simultaneously obtained from a single formulation. The formulation exhibiting the highest tensile strength differed from that providing the highest elongation, while maximum water resistance occurred under different plasticizer conditions. Soil-burial degradation showed yet another compositional response, generally increasing toward rice-flour-rich formulations. These differences demonstrate the existence of a multi-property formulation trade-off.

From an application perspective, maximizing tensile strength alone would therefore be insufficient for selecting an optimum biodegradable straw. Excessive rigidity could compromise flexibility, whereas maximizing elongation could produce a material with inadequate structural resistance. Similarly, water resistance is required to maintain functionality during beverage consumption, but the material should remain susceptible to degradation after disposal [18], [20], [27].

The results further demonstrate that plasticizer identity alone cannot predict overall performance. Glycerol produced the maximum elongation under one formulation condition, whereas sorbitol was associated with the maximum tensile strength under another. Both plasticizers were capable of producing the highest observed water-resistance value under different conditions. Thus, the functional contribution of each plasticizer depended on its interaction with the surrounding rice flour/CMC formulation and its loading [6], [8], [9].

This observation has practical implications for biodegradable-straw formulation. Instead of asking whether glycerol or sorbitol is the "better" plasticizer, a more relevant question is which plasticizer–matrix combination provides the most appropriate balance of properties for the intended application.

Most importantly, the developed formulations demonstrate that in-use functionality and post-use degradation are not necessarily mutually exclusive. Mechanical integrity and resistance to short-term water exposure were achieved while substantial soil-burial mass loss was retained across all formulations. This provides evidence for an in-use durability–post-use degradability balance, which is particularly desirable for biodegradable single-use products.

Therefore, formulation optimization should be approached as a multi-response problem involving simultaneous consideration of mechanical resistance, flexibility, water resistance, and degradation behavior. The present 30-formulation dataset provides a practical basis for identifying such balanced formulations and demonstrates that the performance of rice flour/CMC-based biodegradable drinking straws can be tailored through coordinated adjustment of polymer ratio, plasticizer type, and plasticizer loading.

4. Conclusion

Rice flour/CMC-based biodegradable drinking straws were successfully developed through systematic variation of the rice flour : CMC ratio, plasticizer type, and plasticizer loading across 30 formulations. The resulting materials exhibited tensile strengths of 0.588–3.822 MPa, elongation at break of 12.545–88.964%, water resistance of 25–74%, and soil-burial mass loss of 86.2–100% after 21 days. The highest tensile strength (3.822 MPa) was obtained at a rice flour:CMC ratio of 1:3 with 1.5 mL sorbitol, whereas the highest elongation (88.964%) was achieved at a ratio of 3:1 with 2.0 mL glycerol, demonstrating a clear trade-off between mechanical resistance and flexibility. Water resistance also exhibited a formulation-dependent response, confirming that neither glycerol nor sorbitol was universally superior across the investigated compositions.

More importantly, the formulations retained substantial soil-burial degradation despite achieving measurable mechanical integrity and resistance to aqueous exposure. These findings demonstrate that the functional performance of rice flour/CMC-based biodegradable straws is governed by the combined effects of matrix composition, plasticizer type, and plasticizer loading rather than by a single formulation variable. Therefore, formulation selection should be based on a multi-response balance among mechanical strength, flexibility, water resistance, and post-use degradability, rather than maximizing an individual property. Overall, the developed formulation strategy provides a practical basis for further optimization of biodegradable drinking straws with balanced in-use functionality and post-use degradation.

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