Designing Edible Biomaterials from Agro-Industrial Waste: A Systemic Food Design Approach to Nopal Valorization in Sonsón, Colombia

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Abstract

This study explores the design and development of edible utensils from biomaterials derived from agro-industrial waste generated by nopal (*Opuntia ficus-indica*) cultivation in Sonsón, Colombia. Situated within the fields of Food Design, systemic design, and research-creation, the study addresses the global challenge of reducing single-use plastics while proposing alternative value chains for underutilized agricultural residues.
A systemic design approach structured the research process, encompassing territorial immersion with local communities, biomaterial design and characterization, iterative prototyping, and user-centered evaluation. Nopal cladodes were processed to extract mucilage, which was subsequently combined with natural agents to develop *Nopalia*, a novel edible biomaterial characterized by properties such as hardness, water solubility, biodegradability, and moldability.
This biomaterial enabled the development of *Púa*, an edible skewer conceived not only as a functional utensil but also as a catalyst for richer sensory and cultural food experiences. Qualitative and quantitative analyses were conducted to evaluate material performance, usability, organoleptic attributes, and user perception.

Key words:
agro-industrial waste valorization; edible biomaterial design; Food Design; nopal-based biomaterials; systemic design.

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The results indicate that *Púa* constitutes a viable, sustainable, and experientially meaningful alternative to conventional disposable utensils. Furthermore, the study provides one of the first documented applications of nopal mucilage in the design of edible gastronomic artifacts, extending its use beyond food and packaging applications into the field of product design. The findings highlight the socio-economic and ecological potential of nopal valorization in rural contexts and demonstrate how interdisciplinary, design-driven approaches can generate innovative responses to contemporary environmental and cultural challenges.

Diseño de biomateriales comestibles a partir de residuos agroindustriales: un enfoque de diseño sistémico y Food Design para la valorización del nopal en Sonsón, Colombia

Resumen

Este trabajo estudia el diseño y desarrollo de utensilios comestibles a partir de biomateriales derivados de residuos agroindustriales de cultivos de nopal (*Opuntia ficus-indica*) en Sonsón, Colombia. Situado en la corriente del *Food Design*, el diseño sistémico y la investigación-creación, este trabajo aborda el desafío global de reducir los plásticos de un solo uso, a la vez que propone cadenas de valor alternativas para residuos agrícolas subutilizados. El proceso de investigación tuvo un enfoque de diseño sistémico, incluyendo la inmersión territorial con comunidades locales, el diseño y la caracterización de biomateriales, el prototipado iterativo y la evaluación centrada en el usuario. Los cladodios de nopal fueron procesados para extraer su mucílago, el cual se combinó con agentes naturales para desarrollar «Nopalia», un nuevo biomaterial comestible con propiedades como rigidez, solubilidad en agua, biodegradabilidad y moldeabilidad. Este biomaterial permitió

Palabras clave:
Valorización de residuos agroindustriales, Diseño de biomateriales comestibles, Prácticas de Food Design, Biomateriales basados en nopal, Metodología de diseño sistémico.

el diseño de «Púa», un pincho comestible concebido no solo como un utensilio funcional, sino como un catalizador de experiencias alimentarias sensoriales y culturales. Se realizaron análisis cualitativos y cuantitativos para evaluar el desempeño del material, la usabilidad, las cualidades organolépticas y la percepción de usuarios. Los resultados demuestran que «Púa» constituye una alternativa viable, sostenible y significativa en términos experienciales frente a los utensilios desechables convencionales. Asimismo, el estudio presenta una de las primeras aplicaciones documentadas del mucílago de nopal en el diseño de artefactos gastronómicos comestibles, ampliando su rol más allá de la alimentación y el desarrollo de empaques hacia un ámbito más amplio de diseño de producto. La investigación destaca el potencial socioeconómico y ecológico de la valorización del nopal en contextos rurales y evidencia cómo los enfoques interdisciplinarios, guiados por el diseño, pueden generar respuestas innovadoras a desafíos ambientales y culturales globales.

Introduction

The growing environmental impact of single-use plastics in the food industry has intensified the search for sustainable, biodegradable, and context-sensitive alternatives. Although several studies have examined biopolymers and edible films (Dhumal & Sarkar, 2018; Fabra *et al.*, 2016; Shao *et al.*, 2024; Šuput *et al.*, 2015), a significant gap remains in the integration of agro-industrial waste valorization with systemic design approaches and Food Design practices, particularly in rural contexts where such residues are locally available. Moreover, existing research on nopal (*Opuntia ficus-indica*) has focused primarily on its applications in food, packaging, and biomedical fields (Anchondo-Trejo *et al.*, 2020; González *et al.*, 2025; Herrera-Ibarra *et al.*, 2023; Luna-Sosa *et al.*, 2020;

Torres *et al.*, 2018), leaving its potential as a driver of edible artefact design and culturally meaningful food experiences largely unexplored.

The nopal cactus (*Opuntia ficus-indica*) is widely distributed across the American continent, from Canada to Argentina. It is recognized not only for its adaptability but also for its nutritional properties, as it is rich in fiber, vitamins, and antioxidants and is often regarded as a "superfood" (Ha *et al.*, 2024; Pérez-Álvarez & Ardisana, 2025; Rani *et al.*, 2024). In particular, nopal is strongly linked to Mexican culture, where it is used in food preparations, such as nopalitos, salads, marmalades, sweets, and grilled products, as well as in medicine, construction, art, and crafts (Anchondo-Trejo *et al.*, 2020; Castelán-Urquiza, 2022; Guzmán-Lechuga & Valdéz-Borroel, 2016; Rodriguez-Fragoso *et al.*, 2008; Valdez Cepeda *et al.*, 2008). The plant propagates easily through its root system, which allows growth from both underground and aerial stems. It consists of flattened structures known as cladodes, which form branches and, as they mature, develop into a brown, fiber-rich trunk (Trabelsi & Kammoun, 2020). Its fruit, known as prickly pear, cactus pear, or tuna, is considered exotic in some countries and is produced throughout the plant's life cycle (Albuquerque *et al.*, 2020; Pimienta-Barrios, 1994). In Colombia, particularly in Sonsón, Antioquia, nopal is cultivated mainly for fruit production, which leaves significant volumes of agro-industrial residues underutilized.

Agricultural activities constitute one of the main sources of income for thousands of families in Sonsón. Coffee, avocado, dairy products, and prickly pear are among the most important agro-industrial products in the region (Álvarez *et al.*, 2015; Giraldo Ramírez, 2016). Over the last 110 years, nopal has become a cultural symbol of the municipality. Figure 1 illustrates the agro-industrial origin of the raw material and situates the research within its socio-ecological context, showing traditional nopal crops in the mountains of Sonsón and the harvesting techniques used by farmers to collect prickly pears. Nevertheless, in recent decades, nopal cultivation has declined due to the expansion of monocultures that promise short-term economic returns, generating environmental degradation and socio-cultural loss. Over the last decade, the number of families working with nopal has decreased from 520 to 100 (Agudelo-Gutiérrez *et al.*, 2022), alongside soil nutrient depletion caused by intensive agricultural practices and the progressive erosion of cultural heritage and traditional identity.

Figure 1. Territorial context of nopal production in Sonsón, Antioquia: (a) prickly pear crops in the Alto de Sabanas area and (b) local farmer Ubelio Ospina harvesting cladodes.

An alternative that could support the permanence of nopal in Sonsón is the diversification of economic activities associated with this plant, since all parts of nopal can be used for multiple applications. In previous studies, Pascoe and colleagues examined mucilage extracted from cladodes to develop nopal-based biomaterials as substitutes for single-use plastics (Pascoe-Ortíz *et al.*, 2019; Pascoe Ortíz *et al.*, 2014; Pascoe Ortiz & Mendoza Arce, 2019). Other studies have developed nopal-based edible biofilms for dry food packaging, edible biofilms to extend the shelf life of different chili species, edible coatings that function as pectic agents, and biothreads for medical procedures (González-González, 2011; Guzmán Castillo *et al.*, 2014; Herrera-Ibarra *et al.*, 2023; Luna-Sosa *et al.*, 2020). In Colombia, recent initiatives have explored nopal residues in crafts, product design, and textiles, demonstrating its versatility as a biomaterial (Agudelo-Gutiérrez *et al.*, 2022; Mosqueda-Prado *et al.*, 2024). Despite these advances, limited research has addressed the integration of biomaterial development, product design, and food experience within a systemic and territorial framework.

In this context, Food Design emerges as a critical framework for exploring the relationships among materials, users, and cultural practices, moving beyond purely technical or engineering-driven approaches (Spence, 2022; Zampollo, 2016, 2023). The design of edible materials represents an innovative response to sustainability challenges. By integrating material properties with sensory, symbolic, and experiential dimensions, Food Design enables the creation of products that are not only functional but also culturally meaningful. This work adopts a systemic design approach to generate strategies that may help prevent the loss of nopal crops in Sonsón. Systemic design enables the identification of stakeholders, value chains, and interdependencies across the material, social, and ecological dimensions of the problem (Fassio, 2017; Fitzpatrick *et al.*, 2024; Núñez-Ríos *et al.*, 2020). The research process included: biomaterial extraction and characterization from nopal residues; design and prototyping of edible utensils; and user-centered evaluation through qualitative and quantitative methods.

Accordingly, the objective of this study is to design and evaluate edible utensils derived from nopal agro-industrial waste through a systemic Food Design approach, thereby contributing to sustainable material innovation and the reactivation of local value chains in Sonsón, Colombia. This study provides one of the first documented applications of nopal mucilage in the design of edible gastronomic artefacts. It contributes to the advancement of Food Design by integrating systemic design and biomaterial development within a specific territorial context, while highlighting the potential of this approach as a replicable model across different contexts and latitudes (Reinmuth *et al.*, 2025; Sortino, 2026). Furthermore, it demonstrates how agro-industrial waste can be transformed into culturally meaningful and environmentally sustainable product systems, bridging local knowledge with global design challenges.

Methodology

This research adopts an interdisciplinary approach that integrates design, materials science, gastronomy, and sensory analysis. The collaboration among these domains enabled the articulation of technical material development with the experiential and cultural dimensions of food consumption. Furthermore, the study is framed within a qualitative-interpretive paradigm, as it seeks to understand the systemic relationships among materials, stakeholders, and the context in which they are applied. An experimental-exploratory methodology was employed because the primary objective was to develop and evaluate a biomaterial derived from prickly pear mucilage, optimizing its properties for the manufacture of edible utensils. To achieve this objective, several complementary techniques were implemented, including mucilage extraction and processing, evaluation of thermal and mechanical properties, biodegradability assessments, digital modeling and prototyping, and sensory analysis through affective testing in a gastronomic context.

Mucilage Extraction

The prickly pear samples used in this study were obtained from pruning activities carried out in nopal crops located in Sonsón, Antioquia. Cladodes that were at least two years old and measured approximately 30–40 cm in length, 15–20 cm in width, and 3 cm in thickness were selected to ensure a high content of water and mucilage. Figure 2 illustrates the transformation process through which raw nopal biomass was converted into a usable base material, establishing the foundation for subsequent biomaterial development. The cladodes were cut into pieces measuring approximately 2 × 2 cm and processed using an 800 W commercial juice extractor. The fibrous fraction was separated from the liquid phase, and the extracted mucilage underwent a thermal stabilization process to balance its pH. Specifically, the mucilage was heated in a double boiler at a temperature below its boiling point (80 °C) for 20 minutes. Subsequently, it was removed from the heat, transferred to a clean container, and allowed to settle until decantation occurred. Only the clear fraction of the mucilage was used for subsequent experimentation.

Figure 2. *Cladode processing and mucilage extraction workflow.*

Biomaterials Preparation and Attributes Characterization

Multiple biomaterial formulations were explored using nopal mucilage as the liquid base. The mucilage was combined with different concentrations of edible agents, including honey, sugar, gelatin, starch, and vinegar. Table 1 summarizes the formulations evaluated during the experimental phase.The fabrication process consisted of gradually incorporating the edible agents into the previously prepared mucilage. Ingredients were added one tablespoon at a time and mixed until a thick consistency was obtained. The mixture was then heated in a double boiler over low heat while being manually stirred until it reached a more fluid state. At that stage, vinegar was added, and the mixture was continuously stirred for approximately 15 minutes, or until it thickened again and exhibited a homogeneous appearance.

Table 1. Biomaterial formulations based on nopal mucilage combined with different edible agents

Sample	Mucilage	Honey	Sugar	Gelatin	Starch	Vinegar
N0_1	87%			8%		5%
N0_2	79%		8%	5%		8%
N0_3	87%			4%		9%
N0_4	81%			7%	7%	5%
N0_5	80%	8%		4%		8%
N0_6	70%			10%	14%	6%

The resulting samples were evaluated through a series of technical and sensory tests to determine their suitability for utensil development. As shown in Table 2, the final material selection followed a hierarchical decision process based on hardness, piercing ability, and palatability. A sequential elimination strategy was applied: samples that failed to meet the requirements of a given stage were discarded and were not subjected to subsequent evaluations.

Table 2. Evaluation criteria for biomaterial selection, including qualitative and functional attributes relevant to food design applications.

Type	**Attribute**	**Method**
Physical	Hardness	Evaluated by applying a bending force to the biomaterial in order to assess flexibility and resistance to fracture, ensuring that the material remained sufficiently stiff and did not break easily under stress.
Physical	Cast molding	Assessed by testing the biomaterial's ability to conform to a mold and retain its shape after setting, thereby determining its suitability for controlled shaping processes.
Physical	Piercing ability	Evaluated by applying pressure to determine whether the biomaterial could effectively penetrate food, thereby assessing its feasibility for utensil applications.
Organoleptic	Color	Assessed by evaluating clarity and homogeneous coloration to ensure visual consistency.
Organoleptic	Mild flavor	Assessed by evaluating whether the biomaterial had a mild taste that did not interfere with the flavor of the food.
Organoleptic	Mild odor	Assessed by evaluating whether the biomaterial had a mild aroma that did not interfere with the food's natural scent.
Organoleptic	Texture	Assessed by evaluating whether the biomaterial had a soft and smooth texture that did not interfere with other sensory perceptions.
Biodegradation	Water solubility	Evaluated by submerging a 2 × 2 cm biomaterial sample in a 50 mL beaker.
Biodegradation	Soil degradation	Evaluated by burying a 2 × 2 cm biomaterial sample in soil and monitoring its structural and physical changes over time.

In addition to the qualitative assessments described above, several quantitative and qualitative characterization methods were conducted:

- Hardness: Measured using digital Shore A and Shore D durometers at room temperature.
- Thermal transitions: Evaluated by differential scanning calorimetry (DSC) using a DSC Q200 instrument (TA Instruments). Analyses were performed between −80 °C and 220 °C at a heating rate of 10 °C/min.
- Flame propagation: Assessed through controlled combustion tests conducted in a testing chamber according to ASTM D635-14

Utensil Design Through a Systemic Design Approach

The design of the utensil sought to influence food-related practices by proposing alternative forms of interaction during eating. Ergonomic considerations included finger positioning, utensil length, grip comfort, and the force required to pierce food. To support the design process, a systemic map was developed to identify the relationships among stakeholders, processes, affected groups, users, and functional requirements. This approach facilitated an understanding of the interactions and potential scenarios generated by the product throughout its lifecycle. The systemic map was organized into a series of interconnected phases, which are described in Table 3.

Table 3. Phases of the systemic design approach applied in the study, integrating territorial analysis, material experimentation, prototyping, and user evaluation.

Systemic map phase	Description
Cultivation and harvest	Involves the community of Sonsón, agricultural practices, and nopal farms as the source of raw material.
Research	Refers to the biomaterial laboratory research process and material development activities.
Raw material processing	Considers manufacturing and production plant requirements as a future implementation scenario.
Sales and distribution	Addresses the economic aspects related to product value, distribution, and specialized market positioning.

Systemic map phase	Description
User needs	Considers users' desired experiences and preferences during product selection.
Food consumption	Identifies relevant actors within the gastronomic sector and the contexts in which the utensil may be used.
Waste management	Considers potential procedures for waste disposal and post-consumption management.

Utensils Prototyping and Testing Phases

The prototyping process was structured into a series of iterative phases that integrated exploratory design, material translation, user-centered evaluation, and expert assessment.

Exploratory Design and Form Generation: The design process began with hand-drawn sketches. Through iterative operations involving paper cutting and folding, preliminary formal configurations emerged. This approach facilitated direct engagement with material behavior, allowing form to arise from simple planar transformations rather than predefined geometries. As a result, multiple gripping possibilities were identified. This stage revealed the potential of the object as a skewer-type utensil capable of supporting diverse modes of use and interaction.

Material Translation: Once an initial formal definition had been established, the geometry was translated into a biomaterial-based object through a prototyping process. Early-stage models were first developed in paper and subsequently digitized to generate 3D-printed positive models. These models were then used to fabricate casting molds for the edible biomaterial. The biomaterial was injected into the molds using a manual syringe system, which enabled controlled filling of the cavities. In addition, the drying process was standardized to ensure consistency in the physical properties of the resulting prototypes. This phase established a reproducible workflow that connected digital fabrication techniques with biomaterial processing.

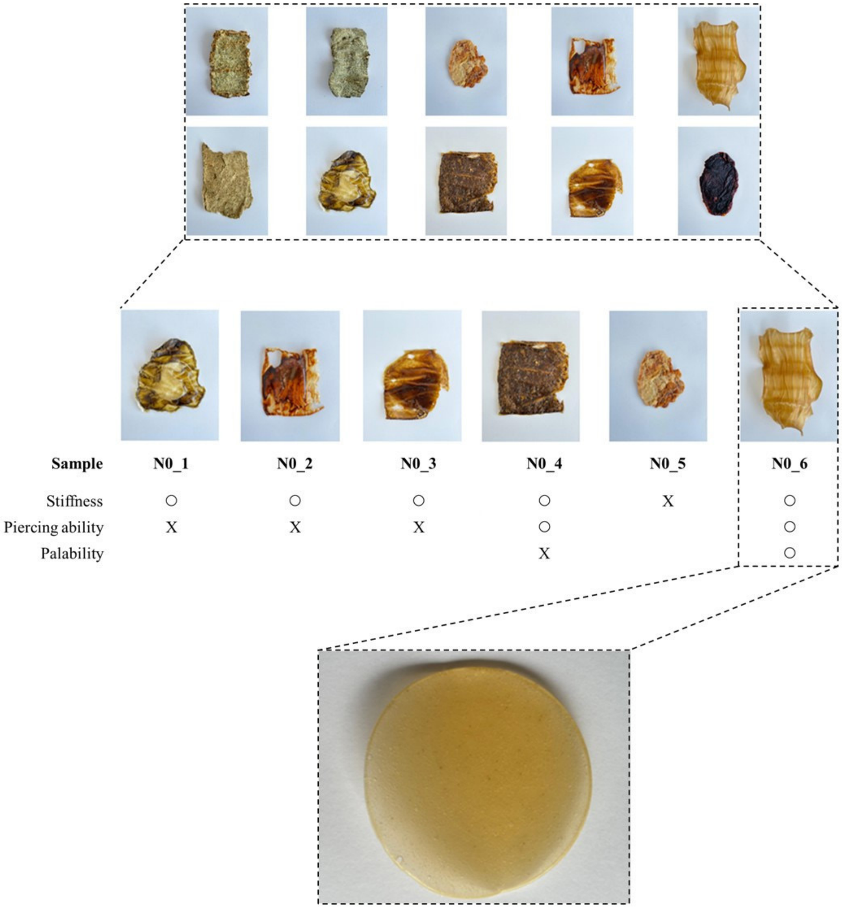
User-Centered Evaluation: High-fidelity prototypes were evaluated through a combined organoleptic and usability testing protocol. The study involved a purposive sample of 20 adult participants between 25 and 32 years of age from Medellín, Colombia. Inclusion criteria required participants to have previous experience in food consumption contexts comparable to those proposed in the study, thereby ensuring their ability to assess both usability and sensory attributes. Exclusion criteria included known food allergies related to the biomaterial components and dietary restrictions incompatible with edible prototypes. Participants were recruited through local networks and academic environments. Participation was voluntary, and informed consent was obtained from all individuals. The organoleptic evaluation focused on flavor, odor, texture, and color, whereas usability testing examined interaction-related dimensions such as grip, affordance, interface, and chewing experience. Together, these assessments provided an integrated understanding of the utensil as both a functional object and an edible artefact.

Expert Evaluation: In addition to user testing, the utensil was evaluated by a culinary expert based in Medellín with more than ten years of experience in the design of creative gastronomic experiences and the reinterpretation of traditional food practices. The evaluation protocol was designed to assess intuitive interaction and the perceived relationship between the object and eating practices. The expert was presented with the utensil alongside food items that varied in thickness, hardness, and consistency. Importantly, no prior information was provided regarding the composition of the biomaterial, its edibility, or the intended use of the object. This procedure enabled an unbiased evaluation of affordance, usability, and conceptual clarity based exclusively on form and interaction.

Results and Discussion

Biomaterial Development Through a Material-Driven Design Approach

Figure 3 presents the biomaterial selection process for edible utensil prototyping within a material-driven design approach (Karana *et al.*, 2015). As shown, multiple iterations were conducted by combining different edible agents with nopal mucilage. These initial explorations resulted in a wide range of colors, textures, and shapes. Based on consistency and visual appearance, six samples were preselected for the initial characterization stage. Their performance was evaluated in terms of hardness, piercing ability, and palatability. When a sample met the evaluation criterion, the corresponding attribute was marked with a circle; when it failed to meet the criterion, it was marked with an X, and the material was discarded from subsequent stages. After the qualitative exploration, sample N0_6 was identified as the material that best met the desired hardness and neutral flavor criteria. In reference to the plant from which it was derived, this material was named "Nopalia." The material combines structural rigidity with a smooth tactile surface and presents a translucent appearance with a light mustard-yellow tone. From an organoleptic perspective, it has a gentle aroma reminiscent of fresh bread and a low-intensity, cereal-like flavor profile similar to fresh pasta dough. These characteristics contribute to a non-invasive sensory presence, supporting its role as an edible interface within the eating experience.



Sample	N0_1	N0_2	N0_3	N0_4	N0_5	N0_6
Stiffness	○	○	○	○	X	○
Piercing ability	X	X	X	○		○
Palability				X		○

Figure 3. Iterative development and selection of "Nopalia": exploration of nopal-based biomaterials using different edible agents and initial characterization.

Biomaterial Characterization

Since all components used to produce "Nopalia" are edible, the resulting material is also edible and suitable for contact with food. Nevertheless, additional technical and sensory attributes must be evaluated before utensil prototyping. Table 4 presents the qualitative and quantitative aspects considered in this study, while the final column reports observations related to each measured attribute.

Regarding qualitative results, the biomaterial was found to be water-soluble: it dissolved completely at 95 °C and partially at room temperature (23 °C). After eight weeks of observation of samples buried in wet soil, evidence of biodegradation was observed in short-term tests, although small fragments of the biomaterial remained. Flame resistance tests showed that "Nopalia" did not ignite or propagate flame. Instead, it formed a char layer that prevented flame propagation, similar to the behavior of flame-retardant materials. The material was also thermoformable when exposed to a heat gun and allowed different shapes to be obtained through cast molding. Overall, it was stiff and partially brittle, as it did not withstand strong impacts, but it exhibited high performance under compressive loads.

Quantitative tests were conducted to assess material performance under controlled temperature and indentation conditions. Thermal transition analysis showed a glass transition temperature at 90 °C. Below this temperature, the material remained in a glassy state, exhibiting solid and rigid behavior that enabled it to retain its shape and perform adequately during eating. Above 90 °C, the material remained solid but became softer, which explains the thermoformability observed in the qualitative tests. Nevertheless, temperatures above 90 °C do not represent a concern for the intended application, since user interaction generally occurs at room temperature, in contact with the human body at approximately 36 °C, and with food at a maximum temperature of 60 °C. When the test reached 180 °C, the material melted, indicating that it can retain its shape up to relatively high temperatures. This result also suggests that "Nopalia" can be melt-molded under controlled temperature conditions, as it behaves as a thermoplastic biopolymer.

Shore hardness is a technique commonly used for polymer and rubber samples and is suitable for measuring surface hardness in biopolymers (Castro *et al.*, 2021; Sadasivuni *et al.*, 2020). The hardness scale ranges from extra-soft and soft to medium-soft, medium-hard, hard, and extra-hard. The material exhibited hardness values of 82.5 Shore A and 72.8 Shore D, indicating that "Nopalia" can be classified as a hard to extra-hard material. These findings are consistent with the qualitative observations. Upon handling, the material feels hard but somewhat brittle. As a general rule, harder materials tend to exhibit greater brittleness.

Table 4. Quantitative and qualitative attributes of "Nopalia", including mechanical, sensory, and functional properties relevant for edible utensil applications.

Test type	Attribute	Yes	No	Value	Comments
Qualitative	Hot-water solubility (95 °C)	x			The material completely dissolves after five minutes.
Qualitative	Room-temperature water solubility (23 °C)	x			The material partially dissolves within one week, leaving small particles in suspension.
Qualitative	Biodegradation in soil	x			The material partially biodegrades within eight weeks.
Qualitative	Flame resistance		x		The flame does not propagate, and the material forms a char layer.

Test type	Attribute	Yes	No	Value	Comments
Qualitative	Sustained combustion		x		The flame is extinguished within a few seconds.
Qualitative	Carbonization	x			After contact with fire, the material carbonizes and turns into ash.
Qualitative	Thermoformability	x			The material can be heat-molded using an industrial dryer or a thermoforming machine.
Qualitative	Cast molding capacity	x			The material can be shaped by pouring the biomaterial into a mold.
Qualitative	Hardness	x			The material is very hard but does not withstand strong impacts.
Quantitative	Glass transition temperature (Tg)			90 °C	Below 90 °C, the material behaves as a rigid solid; above 90 °C, it becomes a softer solid.
Quantitative	Melting temperature (Tm)			180 °C	At 180 °C, the material melts and can be heat-molded, indicating thermoplastic biopolymer behavior.
Quantitative	Shore A hardness			82.5	Hard.
Quantitative	Shore D hardness			72.8	Extra-hard.

Systemic Design Map

The development of a new product involves multiple factors that must be understood as part of an interconnected system. In this context, systemic design makes it possible to examine relationships among stakeholders, processes, interactions, and potential scenarios, thereby facilitating the identification of strategies and opportunities (Barbero & Tamborrini, 2015; Savina & Peruccio, 2020). Figure 4 presents a systemic map in which the edible utensil is positioned at the center and surrounded by the components analyzed throughout the project. The map is organized into four sections according to the similarity and function of the elements involved:

Section a: Cultivation and Research. This section addresses the prickly pear production process and the stakeholders involved in Sonsón, particularly farmers and the local community. It also evaluates how product development may generate economic incentives for prickly pear cultivation through interdisciplinary collaboration.

Section b: Processing and Commercialization. This section includes raw material transformation and food safety standards. It also explores the feasibility of establishing an edible utensil production facility and considers aspects related to marketing, investment, distribution, and potential customers.

Section c: Product Usability. This section focuses on sustainability, gastronomic experience, and consumer perception of innovative products. It is also connected to the food microsystem, as it considers the interaction between the utensil and specific gastronomic events.

Section d: Waste Management. This section proposes two possible end-of-life routes: consumption of the utensil as part of the meal or disposal and biodegradation under natural conditions.

The construction of this map provided a structured pathway to guide the experimental stages of the project across the different disciplines involved. Rather than functioning as a linear representation, the map operated as an integrative framework that enabled a holistic understanding of the system. In this way, each phase of the research could be addressed while considering the multiple actors, processes, and interdependencies that shape the development and potential implementation of the product.

This interdisciplinary approach is central to the project, as it articulates contributions from design, gastronomy, and materials engineering. As argued by Eidler (2024), the intersection between design and gastronomy can serve as a catalyst for rethinking food systems and introducing a transdisciplinary academic dimension to projects such as “Púa.” In this study, this interaction is expanded through the incorporation of materials engineering, which allows technical development, sensory experience, and cultural meaning to be addressed simultaneously.

In this sense, the map not only organizes the research process but also embodies the systemic perspective of the project, enabling the integration of diverse forms of knowledge into a coherent design-driven exploration.

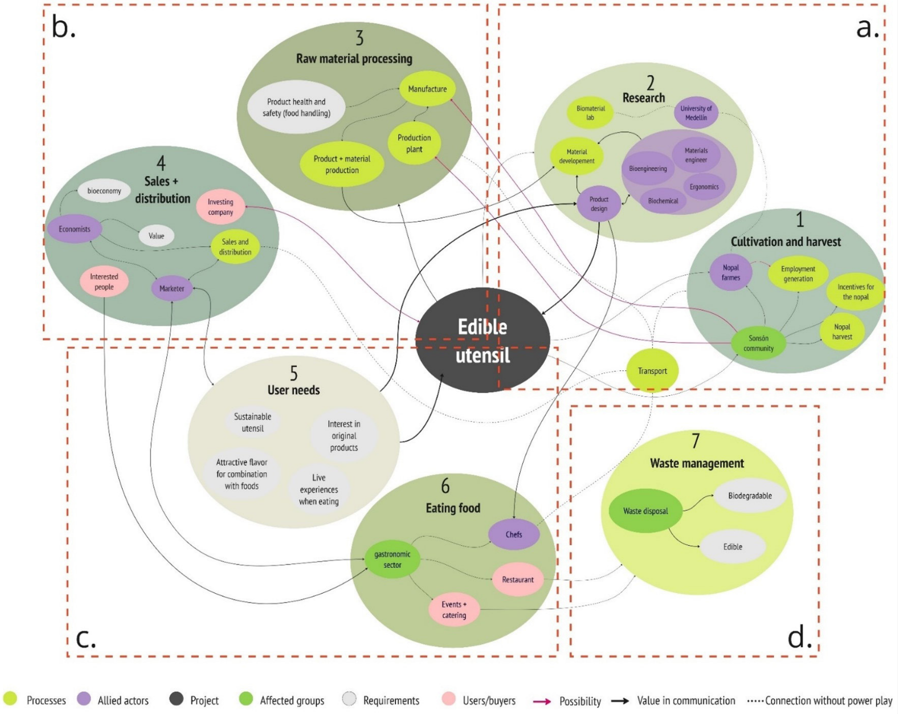


Figure 4. Systemic Food Design map showing the edible utensil as a central element within a network of interconnected stakeholders, processes, and value flows, highlighting its potential social, economic, environmental, and gastronomic impacts.

Utensil Design and Fabrication

The iterative development of the utensil resulted in the progressive refinement of its geometry, ergonomics, and material performance, demonstrating the value of a design-driven and material-informed approach. The utensil was conceived to propose a new way of spearing, holding, and consuming food in small bites, thereby challenging the conventional gesture of picking up food in contexts such as catering. This interaction gives rise to an action that emotionally connects the user with the act of eating. Figure 5a shows the transition from conceptual exploration to tangible form, where cutting and folding operations enabled the exploration of grip configurations, structural behavior, and interaction dynamics. This stage informed the transition from abstract geometries to a functional skewer typology. The designed utensil was named “Púa,” a Spanish word that refers to the spine of the prickly pear cactus. Figure 5 presents the process undertaken to develop the final “Púa” piece, from the reconfiguration of the eating gesture to the final prototypes made with “Nopalia,” the biomaterial created for this exercise. Overall, the process reflects a material-driven and iterative design methodology. Figure 5b presents illustrations of the initial exploratory prototypes, in which a simplified geometry improved usability. The reduction of finger supports led to a cleaner formal language, facilitating a more intuitive grip. The final configuration promotes a holding gesture between the index and middle fingers, intentionally freeing the thumb and moving away from the conventional pinching action typically associated with the consumption of small food portions.

The proposed gesture does not compromise control over food movement or manipulation. Rather, it suggests a choreography of use that focuses attention on the interaction among the hand, “Púa,” and the food. Figure 5c shows the first formal approach to the object, based on a low-fidelity paper prototype. These initial elements made it possible to recognize the proposal’s potential and subsequently control the formal configuration of “Púa” to advance toward the development of a higher-fidelity prototype, as shown in Figure 5d.

The new prototype version of “Púa” was printed in polylactic acid (PLA), which made it possible to evaluate functionality and performance, as the 3D-printed polymer simulated the expected behavior of “Nopalia” within the “Púa” geometry. The curvature of the utensil was progressively refined to establish a continuous and fluid transition from the tip to the finger supports. The supports were widened to improve stability and comfort, ensuring their fit within the first phalanx of the fingers. Simultaneously, the tip evolved from an initially sharp and pointed geometry to a curved profile with a flattened end, improving both safety and functional performance during food penetration.

Although early formal definitions suggested a slender and conical tip, prototyping revealed critical limitations during mold fabrication and material casting. Thin geometries proved structurally fragile and frequently broke during demolding and handling. In response, the morphology was reconfigured into a continuous arched profile with a flat termination. Figure 5e presents the mold and counter-mold created to cast the “Nopalia” biomaterial and obtain a mid-fidelity prototype in the target material, while Figure 5f presents early fabrication trials, highlighting challenges related to material consistency and demolding. These iterations informed subsequent adjustments to material formulation and mold design, contributing to the stabilization of the prototyping process.

The first low-fidelity “Púa” prototype made with the “Nopalia” biomaterial is presented in Figure 5g. This adjustment generated a more structural piece and significantly improved its mechanical resistance. Importantly, this modification did not compromise the utensil’s ability to pierce food; rather, it enhanced durability while maintaining functional performance.

This prototype made it possible to identify that, after removal from the mold, the material contracted, causing the apex to lift and the inner finger support to become more defined. In response, the following parameters were adjusted: the mold should be coated with olive oil and starch; it should be sealed with strong rubber bands to prevent leaks; the material viscosity must be fluid enough to fill the mold without becoming too liquid; gentle tapping is required to prevent air bubbles and help the material fill the cavities completely; and, finally, the drying process should consist of 32 hours inside the mold, followed by demolding and air-drying.

The subsequent prototypes (Figure 5h) showed significant improvement after modifications to the biomaterial. For example, the apex maintained its shape and structure, allowing it to pierce small pieces of food as intended, while the base remained balanced, despite the slight contraction that affected its symmetry. This progress lays the foundation for the industrial scalability of the “Púa” manufacturing process through rigorous, regulated, and standardized procedures that can be further reinforced in laboratory settings.

While the results demonstrate strong potential at the prototype level, scaling the production process remains a significant challenge. Variability in drying conditions, material sensitivity to environmental factors, and the manual nature of the fabrication process require further optimization. Future work should therefore focus on standardizing biomaterial preparation, refining drying protocols, and exploring decentralized production systems. Such approaches could enable local manufacturing in rural contexts, contribute to sustainable value chains, and preserve the ecological and cultural dimensions embedded in the material.

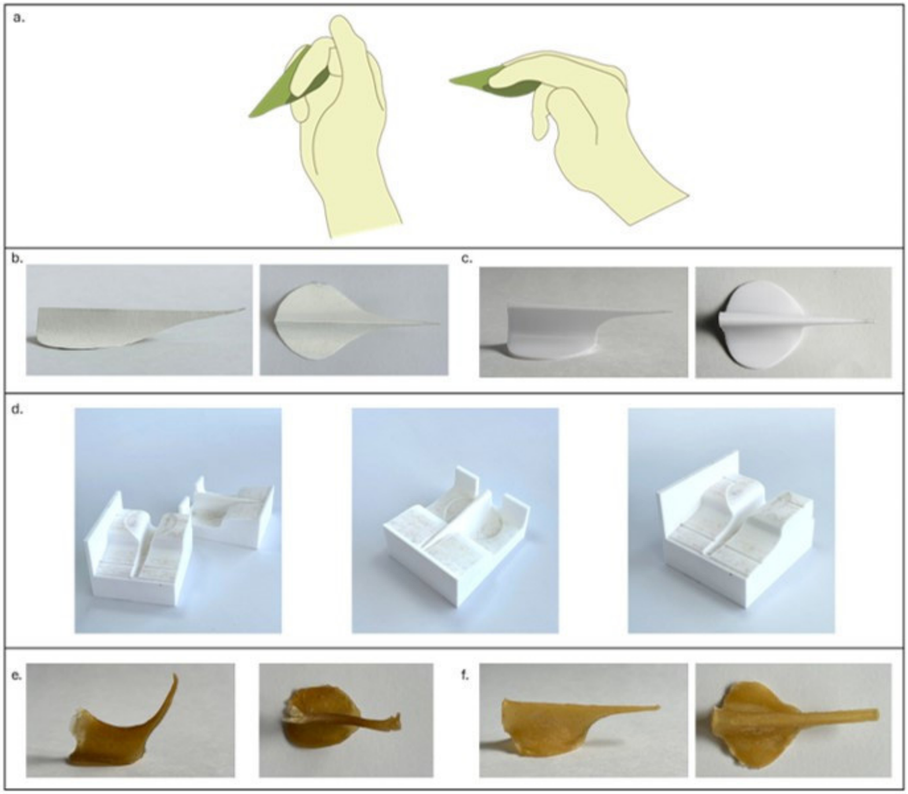


Figure 5. *Design and prototyping process of "Púa": (a) early design exploration, including sketch-based ideation, initial form studies, and paper-based prototyping; (b) grip demonstration diagram; (c) paper-based form exploration; (d) 3D-printed prototype; (e) mold fabrication; (f) initial molding experiments using "Nopalia" and a 3D-printed mold, showing the mold after casting, material adhesion to the mold surfaces, incomplete filling, and a demolded "Púa" prototype with defects such as flash formation and voids; (g) initial biomaterial prototype; and (h) refined "Nopalia"-based artefact.*

User Testing Experience

The final “Púa” prototype successfully fulfilled its intended function as a skewer-type utensil for small food items. Despite morphological modifications driven by material constraints, the rigidity achieved after drying enabled effective food penetration without structural failure.

To conduct the organoleptic and functional evaluations with users of interest, trend analyses were first carried out using the WGSN database to identify potential user typologies for “Púa.” Based on this analysis, the test involved 20 participants interested in culinary experiences, particularly young adults between 25 and 32 years of age who regularly engage in eating experiences that challenge the senses. Additionally, these users were associated with sustainable consumption practices and were aware of the products they use and the waste such products generate.

Figure 6 presents the results of the “Púa” evaluation. The first section shows the attributes assessed. Each circle represents one of the 20 participants. A filled circle indicates a positive evaluation of the attribute, whereas an outlined circle represents a negative evaluation.

For the organoleptic test, participants were instructed to refrain from consuming alcohol, dark beverages, and strongly seasoned or spicy foods before the evaluation. During the test, each participant received two edible pieces of “Nopalia.” The first piece was consumed on its own and could only be accompanied by mineral water. The second piece was paired with green apple, selected because it is a firm and rigid fruit that allowed the utensil’s capacity to pierce and pass through food to be tested.

The organoleptic properties assessed included hand sensation, odor, color, texture, and taste, both alone and paired with food, as shown in Figure 6. The results showed a highly positive evaluation, with 75% acceptance for hand sensation, odor, and color. The flavor of the biomaterial alone received a lower rating, with 65% acceptance, although it remained within the positive range established for the study. Participants reported that the flavor reminded them of raw pasta. They also stated that it did not interfere with the user experience and suggested that it could perhaps resemble the taste of a neutral cookie. In contrast, when the biomaterial was combined with green apple, positive perception increased by 15 percentage points. This suggests that the skewer functions as a central object in the act of eating and may complement the flavor of the food it pierces and holds.

The usability test evaluated attributes related to intuitive use, grip, perceived force required to pierce food, and sensory experience while chewing the material. Participants were asked to interact with the skewer in order to assess its intuitive use, grip comfort, required piercing force, and chewing sensation. During the tests, participants tended to take the object and examine it briefly before manipulating it as suggested. After this initial inspection, they held it between their fingers or "played" with the skewer, attempting to infer its intended purpose, even though apple pieces were included in the test. During this exploratory interaction with "Púa," some participants punctured the fruit with the tip of the object, thereby evaluating the force required to pierce the food and the resistance of the formed biomaterial.

A total of 75% of users considered that piercing the food required less effort than expected, despite the unconventional grip. However, 85% stated that the sensation felt unfamiliar during the first interaction. In contrast, the experience of using and tasting the skewer was entirely new for most participants, according to the comments provided at the end of the test.

Participants emphasized that the flavor of the biomaterial was not strong enough to distract them from the flavor of the fruit, which led to surprise regarding what they were eating. Additionally, most participants (60%) noted that, although the biomaterial itself did not have an intense flavor, chewing it could be somewhat difficult because of its rigidity and crispness. In response to this observation, it may be necessary to reconsider the formal attributes of the skewer, particularly variations in the projection of its apex, in order to preserve its piercing function while reducing discomfort during final consumption. Furthermore, future explorations could examine how the biomaterial behaves over time, considering that it may become less rigid as it comes into contact with moisture from food and the mouth. In this way, the discomfort associated with chewing the entire object could be reduced once its piercing function is no longer required.

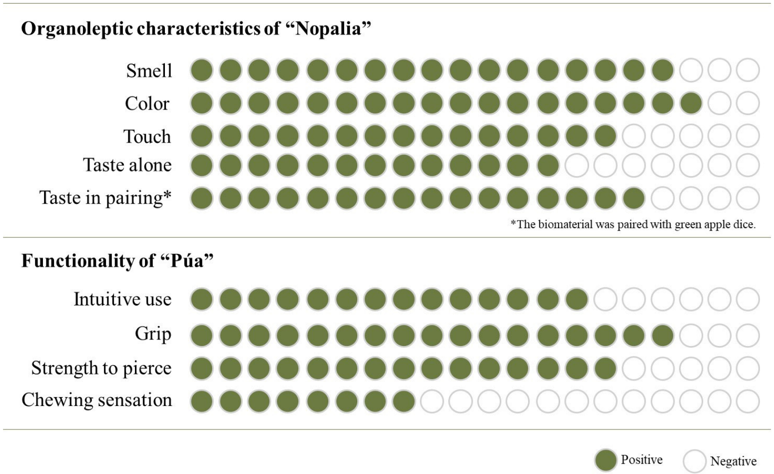


Figure 6. User testing in a relevant context, illustrating interaction dynamics among users, food, and the edible utensil during real-use scenarios.

An additional test was conducted with an expert in creative culinary experiences and a recognized chef in Medellín, Colombia. The session began with a brief pitch in which "Púa" was presented to the expert without prior information about the biomaterial, the intended use of the skewer, or its edibility. Accordingly, the interaction was designed to determine whether the expert could intuitively identify two aspects: what the object was and how it should be handled. The expert immediately interacted with the object by using it to pierce a piece of cheese, green apple cubes, and dates served on a tray (Figure 7a). It took only one attempt for the chef to press the skewer correctly and state that the grip was intuitive. Subsequently, the expert was encouraged to taste a piece of the object, based on the formal and organoleptic properties perceived in the material. After tasting the biomaterial in a single bite, the expert proceeded to experience its flavor in combination with a piece of green apple. Regarding the expert's feedback, it is important to highlight that the subtle flavor of the biomaterial was positively received, as it did not overshadow the food it accompanied.

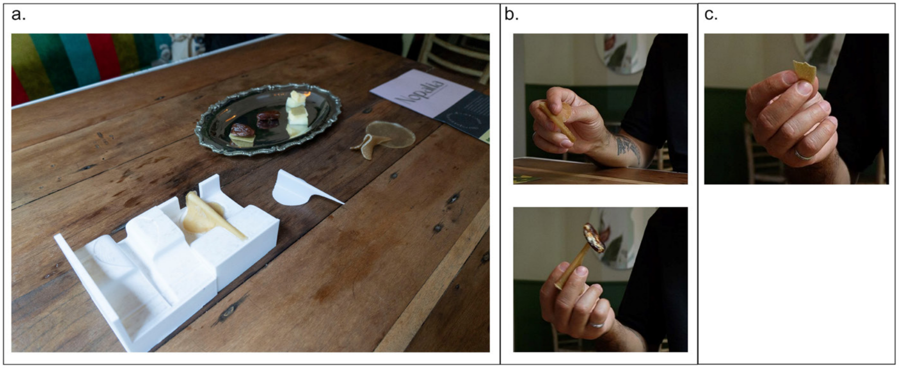


Figure 7. Expert evaluation of "Púa": (a) experimental setup; (b) usability testing through food interaction; (c) sensory assessment of the biomaterial.

The implementation of “Nopalia” in the design of edible utensils highlights how symbolic values can be embedded in physical products to enrich the user experience. User testing demonstrated that the design of “Púa” invites reflection on the act of eating, as diners are encouraged to reconsider the value and role of utensils within the dining experience. In this way, the object promotes a deeper connection with the food consumed and with the surrounding cultural environment.

During the development of the edible utensil prototypes, it was observed that biomaterials such as “Nopalia” can significantly transform eating gestures. Utensils such as “Púa,” designed from this biomaterial, not only introduce a new aesthetic language but also modify the way users physically interact with food. In doing so, they challenge traditional norms of cutlery use and promote a more participatory and sensory experience.

The distinctive texture of “Nopalia,” its subtle aroma reminiscent of freshly baked bread, and its delicate flavor similar to raw pasta are integrated into the eating experience, creating a closer connection with food. This holistic approach extends beyond functionality and fosters a greater appreciation of ingredients, as well as a more conscious and pleasurable culinary experience.

Although user evaluations indicate general acceptance, certain perceptions related to flavor and texture suggest opportunities for improvement. Adjustments in dehydration time, formulation, or the incorporation of natural flavoring agents could enhance the sensory experience and increase user acceptance in broader contexts.

Beyond its functional performance, the value of “Púa” lies in its ability to transform the act of eating into a culturally meaningful and environmentally conscious experience. This positions edible utensils not merely as substitutes for plastic, but as design artefacts capable of redefining human–food–object relationships.

Conclusions

This study demonstrates the potential of nopal agro-industrial waste as a source for the development of edible biomaterials within a systemic and design-driven framework. The resulting material, "Nopalia," and its application in the utensil "Púa," validate a replicable methodology that integrates material experimentation, digitally supported fabrication, and user-centered evaluation.

A key finding is the role of material behavior in shaping form and function, showing how a material-driven design approach can lead to solutions that are both technically viable and experientially meaningful. "Púa" not only fulfills its functional role as an edible skewer, but also reconfigures the act of eating by introducing alternative gestures and fostering more conscious and sensory engagement with food.

The research contributes to Food Design by expanding the application of biomaterials beyond packaging into experiential product design, while highlighting the importance of territorial approaches in connecting local resources with global sustainability challenges.

Although the study is limited by its small sample size, the results indicate strong user acceptance and market potential. Future work should focus on scalability, process standardization, and sensory optimization to support the transition from experimental prototypes to sustainable production systems.

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