sustainability

MDPI

Article

Bridging Nature-Inspired Design Strategies and Consumer Behavior Evidence for Sustainable Circular Packaging: A Concurrent Systemic Framework and Validated Factor Catalog

Andrea Paz Llorens Vargas [1], Juan Carlos Briede Westermeyer [2,*], Marianela Luzardo Briceño [3] and Bernabé Hernandis Ortuño [4,†]

[1] Department of Art and Design Technologies, Faculty of Architecture, Construction and Design, Universidad del Bío-Bío, Concepción 4081112, Chile; allorens@ubiobio.cl
[2] Department of Engineering Design, Universidad Técnica Federico Santa María, Valparaíso 2390212, Chile
[3] Department of Statistics, Faculty of Economic and Social Sciences, Universidad de Los Andes, Mérida 5101, Venezuela
[4] Department of Graphic Engineering, Universitat Politècnica de València, 46022 Valencia, Spain
* Correspondence: juancarlos.briede@usm.cl
† Deceased.

Abstract

Packaging waste represents a critical challenge for Sustainable Development Goal 12: the design stage accounts for approximately 80% of a packaging solution's environmental impact, yet existing circular packaging frameworks evaluate finished solutions rather than guiding the upstream resolution of conflicts among functional performance, sustainability, and consumer interface needs. Nature-inspired design strategies, drawing on 3.8 billion years of biological optimization, offer an inherently circular approach to this challenge but remain methodologically fragmented and disconnected from empirical evidence of consumer behavior. This paper presents the Concurrent Systemic Framework for Sustainable Circular Packaging (CSF-SCP), developed through a six-stage sequential mixed-method process: a systematic literature review (68 publications); in-depth interviews with 11 international experts; a comparative consumer survey (n = 634, Chile/USA/Canada); a commercial packaging field study; and five biomimetic case study analyses. The primary contribution is a validated catalog of 197 nature-inspired design factors across seven operative dimensions, embedded within a concurrent architecture operating simultaneously across Functional, Ergonomic, and Formal subsystems. Consumer evidence reveals that the sustainable packaging attitude–behavior gap is structurally driven by infrastructure accessibility barriers and information deficits, not attitudinal deficiency, directly informing the model's design requirements. Cross-case applicability assessment across five biomimetic design projects demonstrates dimensional coverage of the CSF-SCP's seven-dimension structure. The CSF-SCP provides designers, researchers, and educators with a structured, empirically grounded methodology for sustainable circular packaging design.

Keywords: sustainable packaging design; circular economy; eco-design; consumer behavior; nature-inspired design; biomimetics; concurrent systemic framework; packaging design methodology; design for sustainable behavior; SDG 12

Academic Editor: Grigorios L. Kyriakopoulos

Received: 3 August 2026
Revised: 10 September 2026
Accepted: 8 October 2026
Published: 3 November 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

1. Introduction

Packaging is one of today's most consequential design challenges. Worldwide, the packaging industry generates hundreds of millions of tons of waste annually, with single-use plastics, multi-layer laminates, and non-recyclable composite materials accounting for a disproportionate share of persistent environmental contamination [1]. However, the inadequacy of current packaging design is not merely a waste management failure but rather a failure in the design, the systematic result of design processes that treat sustainability as a downstream constraint rather than an upstream design principle [2,3]. The urgency behind the issue is underscored by ever-accelerating regulatory action: the EU Packaging and Packaging Waste Regulation (2024), Chile's Extended Producer Responsibility Law (Ley REP 20.920), and the No More Bags Act (Ley 21.100) collectively signal that sustainable packaging design is transitioning from a competitive differentiator to a regulatory baseline [4]. These regulatory developments reflect the growing alignment of sustainable packaging with Sustainable Development Goal 12 (SDG 12: Responsible Consumption and Production) and SDG 13 (Climate Action), positioning packaging design not only as a technical challenge but as a lever for the broader sustainable development transition.

Against this backdrop, biomimetics emerges as one of the most promising paradigms for sustainable packaging innovation [5,6]. Living systems have spent approximately 3.8 billion years optimizing solutions to virtually every challenge relevant to packaging: protective containment, structural resilience, selective permeability, material efficiency, sensory communication, adaptive response, and biodegradation [7]. Crucially, biological systems achieve these functions without generating net waste accumulation, operating within closed material loops and renewable energy flows [8]. This intrinsic alignment between biomimetic principles and circular economy imperatives positions biomimetics not merely as a source of formal inspiration, but as a strategic methodology for designing inherently circular packaging systems.

The scientific community has recognized this potential. Research on individual biomimetic applications to packaging has grown substantially: mycelium-based composites replacing expanded polystyrene [9], PLA-based films inspired by plant leaf architecture demonstrating simultaneous mechanical performance and soil biodegradability [10], nature-derived hierarchical geometries for structural lightweighting [11], and biomimetic functional food packaging with barrier, antioxidant, and intelligent properties [12]. Despite this accumulated knowledge, a critical gap persists: no operational design framework has yet integrated these biomimetic strategies into a coherent, packaging-specific, empirically grounded design tool.

As illustrated in Figure 1, this gap operates at three interconnected levels, each separately acknowledged in the literature but never previously addressed in combination.

1.1. Gap 1—Methodological Fragmentation in Biomimetic Design for Packaging

Existing biomimetic design frameworks are either domain-general [13–15] or domain-specific to isolated strategies [16,17]. An analysis of biomimetic tools across industrial sectors confirmed that packaging remains one of the domains where biomimicry application is still nascent [15]. The most rigorous systematic review of circular packaging design frameworks found that nature-inspired approaches are referenced but not integrated into any coherent operational design tool [2]. In fact, a 2025 design framework study explicitly identified the core problem as "conflicts between circularity/sustainability and functional requirements and inadequate tools to provide packaging-specific practical solutions" [3].

https://doi.org/10.3390/su182111224

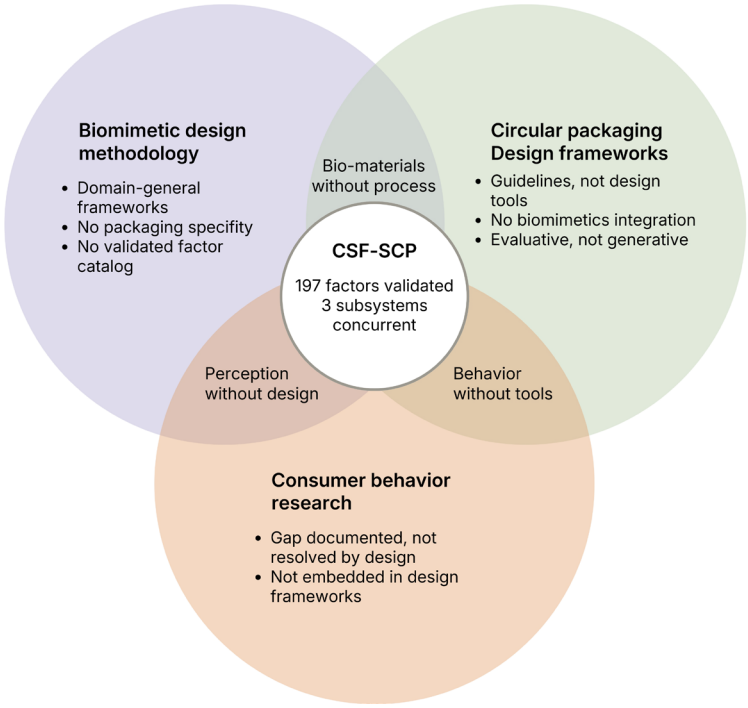


Figure 1. The triple research gap: three bodies of literature with independent contributions and unaddressed intersections. The CSF-SCP occupies the center space that no prior framework has addressed. Source: prepared by the authors.

1.2. Gap 2—Missing Empirical Grounding in Consumer Behavior: A PRISMA-Based Systematic Review Encompassing 78 Publications [18] Confirmed a Universal Attitude–Behavior Gap

High sustainability awareness does not necessarily lead to sustainable purchasing or disposal behavior. A landmark review of 232 green consumer behavior studies [19] identified a lack of knowledge, cost, and limited availability as primary barriers. Crucially, research shows that unfamiliar aesthetic features reduce the willingness to pay even when detailed environmental information is provided, with "first impressions prevailing over cognitive reformulations" [20], and without this evidence included in the design requirements, biomimetic frameworks risk producing technically sophisticated solutions that fail at the consumer interface.

1.3. Gap 3—Absence of a Concurrent, Multi-Subsystem Integration Architecture

Most existing packaging frameworks "primarily evaluate and rank existing solutions rather than providing design guidance for resolving conflicts between functional and sustainability requirements" [3]. This sequential orientation prevents the generative integration that characterizes successful biomimetic design, in which multi-dimensional biological strategies must be simultaneously operationalized across material, structural, ergonomic, and formal design requirements.

The Concurrent Systemic Framework for Sustainable Circular Packaging (CSF-SCP) presented in this paper addresses all three gaps through a single, integrated contribution. Building on Hernandis's concurrent systemic design methodology [21,22], the CSF-SCP embeds 197 validated biomimetic factors across seven operative dimensions within a packaging-specific concurrent design architecture, grounded in empirical evidence from consumer behavior. This paper makes three distinct contributions: (a) the most comprehensive empirically validated classification of biomimetic design resources applicable to packaging; (b) cross-cultural consumer behavior evidence translated into operative design

requirements; and (c) the CSF-SCP as an integrated concurrent design framework validated through five real-world biomimetic case studies.

2. Background and Theoretical Framework

2.1. Biomimetic Design Methodology: Advances and Gaps

Biomimetics is based on the principle that evolutionary selection has converged on highly optimized solutions analogous to those faced by designers [5,7]. Benyus [5] articulated three operative levels of biomimetic abstraction: the organism level (form mimicry), the behavioral level (process emulation), and the ecosystem level (systemic circular principles). A typological analysis distinguished six different biomimetic design approaches with different conceptual assumptions, confirming that the field lacks an integrative architecture capable of managing these types concurrently [16]. In practice, biomimicry is frequently reduced to the formal and material mimicry of isolated biological features rather than to the systematic application of strategies [8].

Domain-specific biomimetic applications confirm both the potential and the methodological gap. A biologically inspired workflow for tea packaging recently combined three structured design tools, affinity diagrams (a qualitative grouping method), Quality Function Deployment or QFD (a matrix-based tool for translating customer requirements into design specifications), and grey relational analysis (a multi-criteria decision-making technique), to guide biomimetic packaging decisions [23]. While innovative, this approach addresses a single product category and does not generalize to the broader packaging design domain.

2.2. Circular Packaging Design: Frameworks Without Biomimetics

The most comprehensive systematic review of circular packaging design [2] confirmed that upstream design decisions are primary determinants of circular performance. A review of bio-based food packaging [24] corroborated this regarding the material dimension. Critically, both reviews find that nature-inspired strategies are referenced as potential solutions but not integrated into any operational design methodology. A 2025 circular packaging design framework review explicitly identified the core unresolved problem: conflicts between circularity/sustainability requirements and functional requirements, and the absence of practical, packaging-specific solutions [3]. A review of circular design guidelines confirmed that "the implementation of circular guidelines faces challenges, particularly the lack of appropriately tailored information that is accessible to designers" [25]. The gap between available biological design knowledge and its practical integration into packaging design tools is thus empirically confirmed at the level of the framework.

2.3. Consumer Behavior: Structural Gap Evidence

A PRISMA-based review of 78 peer-reviewed publications [18] found that consumers are willing to pay a 10–20% premium for sustainable packaging but are constrained by three primary barriers: limited environmental knowledge, the price premium of sustainable alternatives relative to conventional plastic packaging (typically 20–50% higher), and perceived risk of performance trade-offs. These barriers operate across income levels, though their relative weight varies by socioeconomic context: in emerging markets, price sensitivity is the dominant constraint, while in higher-income contexts, information deficits and habitual purchasing patterns play a larger role. A landmark review of 232 green consumer behavior studies [19] identified lack of knowledge, price premiums, and perceived risk as the primary barriers. Crucially, research shows that unfamiliar aesthetic features reduce willingness to pay even when detailed environmental information is

provided, with 'first impressions prevailing over cognitive reformulations' [20], and without this evidence included as part of the design requirements, biomimetic frameworks risk producing technically sophisticated solutions that fail at the consumer interface.

Regarding biomimetic aesthetic perception specifically, Luo et al. [26] found that biomimetic experience, defined as the consumer's perception of nature-inspired design qualities in packaging, was a significant positive mediator of sustainable packaging adoption, with stronger effects observed among younger consumers. Lisboa et al. [27] similarly documented an attitude–behaviour gap among younger consumers regarding sustainable packaging adoption, finding that positive sustainability intentions do not reliably translate into purchase behaviour. This finding provides empirical support for the CSF-SCP's Formal subsystem as a functional, not merely aesthetic, design requirement. It is noted that this evidence is drawn from a study of younger consumers and does not characterize the age profile of the present study's sample, which is discussed in Section 3.5.

2.4. Concurrent Systemic Design: The Methodological Foundation

The concurrent systemic design model developed by [21,22] conceptualizes design as the simultaneous management of three fundamental subsystems: Functional (material properties, technical performance, production processes), Ergonomic (user interaction, accessibility, usability, and ease of disposal), and Formal (aesthetic qualities, morphological language, and communicational attributes). This is not a process preference but a design epistemology: optimal solutions emerge from managing subsystem interdependencies rather than resolving them sequentially. The CSF-SCP applies this architecture to biomimetic sustainable packaging for the first time, establishing the seven biomimetic factor dimensions as operative variables within the subsystem structure.

2.5. The Intersection: Three Gaps, One Framework

Table 1 maps the four bodies of literature reviewed above and the CSF-SCP's contribution. Each domain has generated substantial knowledge while leaving critical intersections unaddressed.

Table 1. Research gap mapping: existing contributions and unaddressed intersections across the four foundational domains of the CSF-SCP. Source: prepared by the authors.

Research Domain	What Exists	What Is Missing	Key References
Biomimetic design methodology	Typologies, sector tools, domain-specific workflows	Packaging-specific, multi-dimensional, validated factor catalog	[1-4,8,10,12,13,15,16,23,28]
Circular packaging design	Guidelines, checklists, evaluation frameworks, PPWR compliance	Actionable upstream design tool integrating biomimetics; conflict resolution	[2-4,24,25,29]
Consumer behavior research	Gap documentation; barrier ID; WTP studies; label effectiveness	Behavioral evidence as operative design requirements within design frameworks	[3,6,18-20,26,30,31]
Concurrent systemic design	Multi-subsystem concurrent architecture; validated in industrial products	Application to biomimetic sustainable packaging; circular economy integration	[21,22,31,32]
CSF-SCP (this paper)	First integration of all four domains in a single operational packaging design framework	Addressed by this paper	This study

3. Materials and Methods

3.1. Research Design

The CSF-SCP was developed through a six-stage sequential mixed-method design (Figure 2), in which each stage builds upon and is informed by the evidence generated in preceding stages. This triangulation strategy ensures the framework is simultaneously grounded in scientific literature, validated by domain expertise, empirically contextualized by evidence from consumer behavior, and confirmed by real-world application cases.

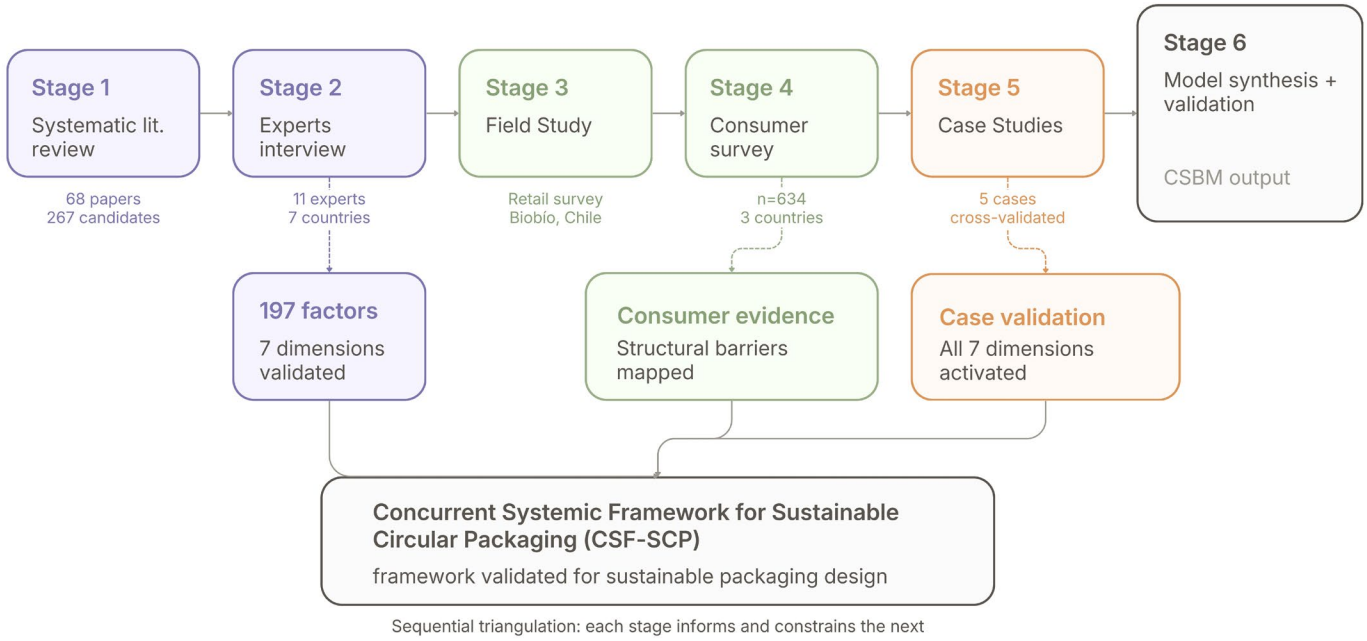


Figure 2. Six-stage sequential mixed-method research design. Each stage's primary output feeds into subsequent stages and ultimately into the model's synthesis. Colors denote parallel evidence streams: purple = expert-validated design knowledge (Stages 1–2); green = consumer behavioral evidence (Stages 3–4); orange = applied case validation (Stage 5); dark outline = model synthesis (Stage 6).Source: prepared by the authors.

3.2. Stage 1: Systematic Literature Review

A PRISMA-informed systematic review was conducted in January 2024 across three bibliographic databases: Web of Science (WoS), Scopus, and SciELO. The following search string was applied in WoS and Scopus (adapted for SciELO): ("biomimetics" OR "biomimicry" OR "bioinspired design" OR "bionic design" OR "nature-inspired design") AND ("sustainable packaging" OR "circular packaging" OR "eco-design" OR "packaging design" OR "packaging sustainability"). Searches were conducted in the Title, Abstract, and Keywords fields with no temporal restriction to preserve access to foundational works (e.g., Benyus, 1997 [5]). Language was restricted to English and Spanish.

The screening process, documented in Figure 3 (PRISMA flow diagram), proceeded as follows: (1) identification: 312 records retrieved (WoS: 147; Scopus: 134; SciELO: 31); (2) deduplication: 89 duplicates removed, yielding 223 unique records; (3) title/abstract screening: 223 records screened; 117 excluded (not addressing biomimetics in design applications, or not addressing packaging or sustainable product design); (4) full-text eligibility assessment: 106 full texts assessed; 38 excluded (22 purely biological studies without design application, 11 non-indexed conference proceedings, 5 unavailable full texts); and (5) inclusion: 68 publications included in final synthesis.

Inclusion criteria were: (a) indexed peer-reviewed publications or book chapters; (b) direct relevance to biomimetics, biomimicry, or bioinspired design applied to product design, packaging, or materials; and (c) availability of full text. Exclusion criteria were: (a) purely biological studies without a design application component; (b) non-indexed sources; (c) duplicate records; or (d) papers addressing biomimetics exclusively in architecture or urban planning without transferable design principles.

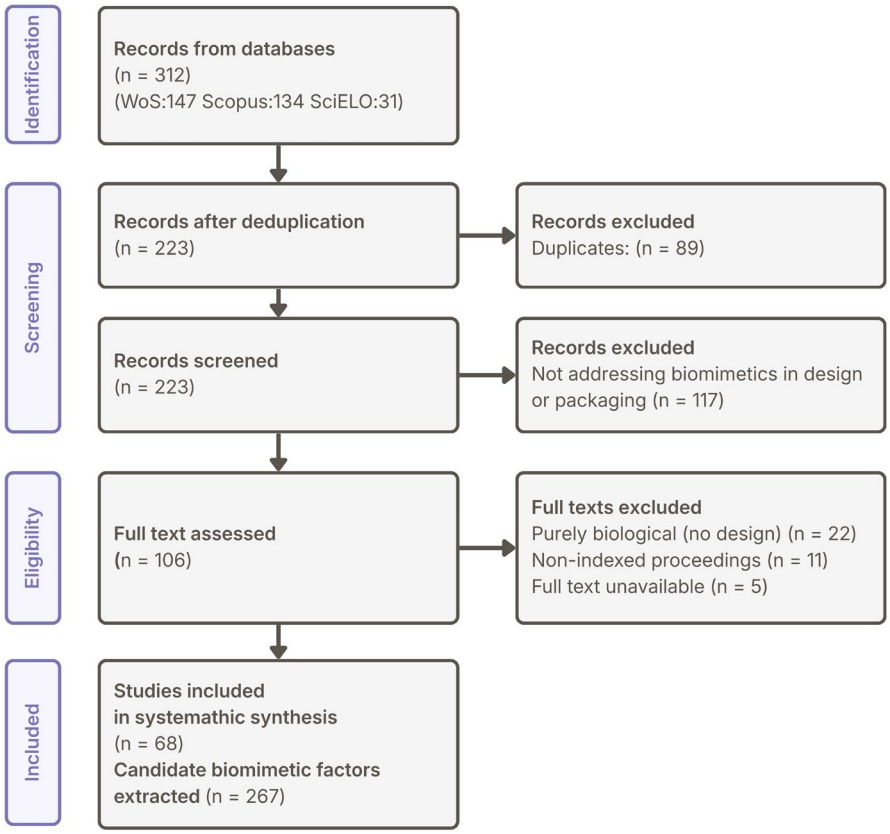


Figure 3. PRISMA flow diagram of the study identification, screening, eligibility assessment, and inclusion process for the systematic review of biomimetics in design and packaging. Source: Prepared by the authors.

Coding procedure: Each of the 68 selected publications was systematically coded by the first author using a structured extraction form to identify all biomimetic factors, principles, and concepts referenced that were applicable to design or packaging. Codes were organized into a matrix (with publications as rows and candidate factors as columns). This process yielded 267 candidate terms. Synonymous and overlapping terms were consolidated through iterative discussion between the two senior authors (A.P.L.V. and B.H.O.), reducing the working inventory to a structured list of candidate factors for expert review in Stage 2.

3.3. Stage 2: Expert Interviews

Eleven internationally recognized experts in biomimetics, bionics, and sustainable design were recruited through purposive sampling, applying three selection criteria: (a) demonstrated research or professional practice in biomimetics, bioinspired design, or sustainable product design, evidenced by peer-reviewed publications or internationally recognized projects; (b) active professional or academic involvement at the time of this study; and (c) geographic and disciplinary diversity to ensure varied perspectives. The resulting

panel comprised: Carmelo di Bartolo (Industrial Design, Italy), Sergio Grijalva (Industrial Design, Mexico), Tomás Dorta (Architecture and Industrial Design, Canada), Jimena Alarcón (Product Design, Chile), Kazmy Chi Muñoz (Architecture, Mexico), Juan Carlos Briede (Industrial Design, Chile), Alejandro Zuleta (Materials Engineering, Colombia), Elvert Duran (Industrial Design, Chile), David Torreblanca (Industrial Design, Colombia), Gino Ormeño (Industrial Design, Chile), and Rosario Villegas (Industrial Design, Chile).

A 12-question semi-structured protocol was applied via Google Forms and videoconference between March and June 2024. The protocol comprised two parts: Part 1 (Questions 1–4) explored experts' general conceptions of biomimetics as a design methodology and its relationship to sustainable packaging; Part 2 (Questions 5–12) presented the candidate factor dimensions derived from Stage 1, asking experts to: (a) rate relevance on a 5-point Likert scale; (b) identify factors considered redundant or poorly defined; (c) propose additional factors; and (d) suggest reclassifications across dimensions.

Coding and decision procedure: expert responses were organized in a structured coding matrix. For each factor, the following decision rules were applied: (1) factors rated relevant (score ≥ 4) by eight or more experts (≥73%) were retained; (2) factors rated redundant or poorly defined by five or more experts were reviewed for removal or consolidation; (3) factors proposed by three or more experts were added; and (4) reclassification proposals were implemented when supported by at least three expert opinions. These procedures resulted in: 31 factors removed, 17 factors added (including mono-material design, proposed unanimously as a design-domain analog of biological material economy), and dimensional reorganization of 12 items, yielding the final catalog of 197 content-validated biomimetic factors across seven dimensions.

Content validity was assessed using the Content Validity Index at the item level (I-CVI), calculated as the proportion of experts who rated each item as relevant (scores 4 or 5). The mean I-CVI across the 197 retained factors was 0.84 (SD = 0.09), exceeding the 0.78 threshold recommended by Lynn [33] for panels of 6–10 experts and the 0.83 threshold for panels of 11 or more. The term 'content-validated' is used throughout this paper to reflect expert agreement on the relevance and appropriateness of factors, not experimental or predictive validation of the framework's performance in practice.

3.4. Stage 3: Commercial Packaging Field Study

Direct observation and photographic documentation were conducted across a stratified sample of supermarkets and retail establishments in Chile's Biobío region, supplemented by Internet-based research. Packaging specimens were classified by material family, commercial tier, and sustainability attributes (recyclability, biodegradability, sorting guidance. The field study sample was stratified by retail market segment: three large-format hypermarkets (upper-middle- and upper-income market), three supermarkets (middle-income market), and two discount/neighborhood stores (lower-middle-income market), all located in the Concepción metropolitan area of Chile's Biobío region. A total of 847 packaging specimens were documented across the eight establishments. Online research extended the typological inventory to include 63 internationally marketed packaging solutions relevant to the biomimetic or sustainable packaging domain.

3.5. Stage 4: Consumer Survey

Questionnaire development: the 25-item survey instrument was developed in three stages. First, items were generated from thematic domains identified in the literature review: sustainable packaging familiarity, environmental impact in purchase decisions, post-consumer disposal behaviors, responsibility attribution, willingness to pay, material preferences, and information sources for sustainability assessment. Second, items were reviewed for content and face validity by three researchers with expertise in survey

methodology and sustainable consumption, resulting in the consolidation of 32 draft items into 25 final items (12 single-response, 10 multiple-response, 3 Likert-scale; 1 = strongly disagree, 5 = strongly agree). Third, a pilot test was conducted with 18 participants in Concepción, Chile, to assess item clarity and average completion time (12–15 min). Minor wording adjustments were made based on pilot feedback. Willingness-to-pay items were additionally informed by Herrmann et al. [34], who found that sustainability perceptions and willingness to pay for sustainable food packaging are jointly shaped by environmental concern and packaging aesthetics.

Language equivalence: the Spanish-language version (Chile) was developed as the primary instrument. English and French translations for the USA and Canada comparison group were produced by bilingual researchers fluent in both academic and everyday language. Back-translation verification was conducted for the English version; conceptual equivalence rather than literal translation was prioritized, consistent with established cross-cultural survey methodology.

Sampling: the survey was distributed via snowball sampling, initiated by the research team through professional and academic networks in the Biobío and Ñuble regions of Chile, as well as equivalent networks in the USA and Canada. Seed participants were professionals in design, education, health, and public administration, a deliberate choice intended to capture primary household purchase decision-makers rather than a student convenience sample. We acknowledge that snowball sampling does not generate a probability sample. The cross-country analysis is therefore presented as exploratory and descriptive, not as a basis for inferential cross-national comparisons. Case study selection for Stage 5 (Section 3.6) followed purposive sampling criteria established by Yin [35], ensuring theoretical relevance and representativeness across biomimetic design applications.

Sample age profile and rationale: the modal age cohort in the Chilean sample was 40–69 years (64.9%), reflecting the demographic profile of primary household purchase decision-makers in Chilean households, where adults over 40 are disproportionately represented as the main grocery purchasers (INE Chile [36]). Research consistently shows that older adult consumers demonstrate stronger environmental consideration and greater attention to packaging sustainability in purchasing decisions than younger cohorts (Zsóka et al. [37]; Petkowicz et al. [38]). The Generation Z reference in Section 2.3 refers specifically to published findings on biomimetic aesthetic perception [26], not to the age profile of the present sample.

3.6. Stage 5: Case Study Analysis

Five biomimetic design projects were selected through purposive sampling: MycoComposite™ (Ecovative Design), Freshdy™ for Longer (Grupo Sinekis), BUGA Fiber Pavilion, Piñatex (Ananas Anam), and biomimetic UAV drones. Each was analyzed through a three-stage protocol comprising project description, biomimetic analysis (biological model, abstracted principles, design translation), and factor integration mapping against the CSF-SCP dimensions (Table 2). The five cases were coded by the first author (A.P.L.V.) using a structured protocol. Activation of each CSF-SCP dimension was assessed as follows: primary activation (●●) was assigned when a biomimetic strategy constituted a core design driver mapping directly onto a dimension; secondary activation (●) when a dimension was engaged but not as a primary driver; non-activation (–) when no traceable biomimetic strategy could be identified. A second independent review of the coded matrix was conducted by the second author (J.C.B.W.) for three of the five cases; no substantive disagreements were identified. Full dual coding of all five cases was not conducted; this limitation is acknowledged in Section 5.4.

Table 2. CSF-SCP factor dimension activation matrix across five biomimetic case studies with biological models. Source: Prepared by the authors.

Case Study	Form/ Morphology	Comm./ Perc. Q.	Geometry/Order	Material	Structure/Constr.	Process/Adapt.	*n*
MycoComposite™ (Ecovative) Biological model: fungal mycelium growth and network architecture	●	–	●	●●	●●	●●	6
Freshdy™ for Longer (Sinekis) Biological model: maize husk, onion, and garlic multilayer moisture regulation	–	–	●	●	●●	●●	5
BUGA Fiber Pavilion Biological model: sea urchin skeleton, hierarchical double-curved shell geometry	●●	–	●●	●	●●	–	5
Piñatex (Ananas Anam) Biological model: pineapple leaf fiber cellular architecture and agricultural loop	●	●	–	●●	●	●●	6
Biomimetic UAV drones Biological model: bird and insect wing aerodynamics and kinematics	●●	–	●	–	●●	●●	5

●● = primary design driver; ● = secondary activation; – = not prominently activated; *n* = total dimensions activated. Comm./Perc. Q. = Communication/Perceived Quality; Process/Adapt. = Processes/Adaptability/Symbiosis (includes Function/Strategy/Mechanisms).

3.7. Stage 6: Model Synthesis and Validation

The CSF-SCP was synthesized by integrating the validated biomimetic factor inventory with Hernandis's concurrent systemic architecture [21,22] and sustainability/circular economy variables. Model variables were classified as entry variables (market context, regulatory requirements, consumer behavior evidence, biomimetic factor library), subsystem variables (functional, ergonomic, formal parameters), and output variables (sustainability performance, circularity, innovation quality, user experience). Theoretical validation was achieved through convergent integration of all data streams; empirical validation through the five case study analyses.

3.8. Validation Logic

The validation strategy adopted in this study relied on methodological triangulation. Biomimetic factors were identified through a systematic literature review, refined through expert assessment, and subsequently contrasted against real-world biomimetic applications. The convergence of these complementary evidence sources supports the content's validity and practical applicability of the resulting 197-factor catalog.

During the preparation of this manuscript/study, the author(s) used [Claude Sonnet 4.6, Anthropic] for the purpose of [development of draft visual representations of figures]. The authors have reviewed and edited the output and take full responsibility for the content of this publication.

4. Results

4.1. The Validated Biomimetic Factor Catalog

4.1.1. Factor Identification from Literature

A systematic analysis of the 68 selected publications produced a consolidated inventory of biomimetic factors spanning the full range of design-relevant biological strategies. The frequency analysis revealed that the most consistently referenced factor clusters were morphological adaptation, material properties, structural organization, and functional strategy. A significant finding was the high frequency of references to geometric and organizational principles, such as Voronoi tessellation, fractal structure, hierarchical organization, and Fibonacci-based spiral forms, which appeared as operative design factors in over 60% of the reviewed publications. This finding motivated the preliminary identification of a dedicated Geometry/Order/Organization dimension within the emerging factor structure. The relevance and conceptual boundaries of this dimension were subsequently examined and refined through expert validation.

4.1.2. Expert Validation and the Final Seven-Dimension Framework

Following expert consultation, the final content-validated catalog comprises 197 biomimetic factors distributed across seven dimensions. Table 3 presents the dimensional structure, along with representative factors and their relevance to primary packaging design.

Table 3. Validated CSF-SCP factor catalog: seven dimensions with representative biomimetic factors and packaging design relevance (n = 197). Source: adapted from [21]; prepared by the authors.

Dimension	*n* Factors	Representative Biomimetic Factors	Primary Packaging Design Relevance
Form/ Morphology	31	Biomorphic geometry, adaptive shell form, camouflage, surface texture, protective curvature, aerodynamic profile, mimicry	Structural optimization, impact resistance, brand differentiation, formal innovation
Communication/Perceived Quality	28	Color signaling, ripeness indicators, aposematism, pattern communication, species identification, sensory cues	Consumer perception, shelf impact, intuitive quality and safety communication
Geometry/Order/Organization	26	Voronoi tessellation, fractal patterns, hexagonal arrays, spiral organization, Fibonacci sequences, hierarchical nesting	Material efficiency, load distribution, lightweighting, aesthetic differentiation
Material	32	Biodegradability, bio-based origin, biomineralization, monomaterial design, hydrophobicity, self-healing, compostability, biocompatibility	Circular end-of-life, material loops, regulatory compliance, food safety
Structure/ Construction	30	Multilayer architecture, gradient materials, microporosity, interlocking mechanisms, hierarchical construction, lattice structures	Protective function, weight optimization, design for disassembly, circularity
Processes/ Adaptability/Symbiosis	29	Self-assembly, self-repair, adaptive environmental response, gas exchange regulation, humidity control,	Active packaging, extended shelf life, environmental responsiveness, end-of-life management

		photodegradation, composting kinetics	
Function/ Strategy/ Mechanisms	21	Protection strategy, selective permeability, hygroscopic actuation, energy efficiency, containment mechanisms, closing/opening functions, load transfer	Core packaging function, user interaction, technical performance, innovative mechanisms
Total	**197**		

A key outcome of expert consultation was the inclusion of monomaterial design as a factor within the Material dimension. Although monomaterial construction is not a biological property per se, experts unanimously argued it represents the closest operational analog in packaging design to the biological principle of material economy, the tendency of living systems to achieve functional complexity with the minimum number of distinct materials. This cross-disciplinary bridging is independently supported by Zhu et al. [2] and Markevičiūtė et al. [24], who identify monomaterial construction as the single design decision with the highest impact on recyclability and circular material recovery.

4.2. Consumer Survey Results

4.2.1. Sample Profile and Demographic Summary

Table 4 summarizes the demographic characteristics profile of the survey participants. The Chilean sample (n = 530) was predominantly female (74.0%) and concentrated in the 40–54 (28.1%) and 55–69 (36.8%) age groups. A high proportion of respondents reported university or postgraduate education (72.1%), and most identified themselves as the primary household purchase decision-maker (77.9%). In addition, approximately two-thirds of respondents reported being married or living with a partner (64.1%). Similar demographic tendencies were observed in the USA (n = 51) and Canada (n = 53), where respondents were also predominantly female, highly educated, and actively involved in household purchasing decisions. These characteristics underscore the sample's relevance for exploring consumer perceptions and behaviors related to sustainable packaging.

Table 4. Consumer survey sample demographic profile and expert panel summary. Source: prepared by the authors.

Demographic Variable	Chile (n = 530)	USA (n = 51)	Canada (n = 53)
Gender: female	74.0%	78.4%	77.4%
Age cohort: 40–69 years (modal)	64.9%	70.6%	62.3%
University graduate or higher	72.1%	84.3%	88.3%
Primary household purchase decision-maker	77.9%	92.1%	94.3%
Married/living with a partner	64.1%	66.6%	73.5%

4.2.2. The Attitude–Behavior Gap and Structural Barriers

Figure 4 presents the key findings from the consumer survey across all three national samples, organized to highlight the attitude–behavior gap and its structural drivers.

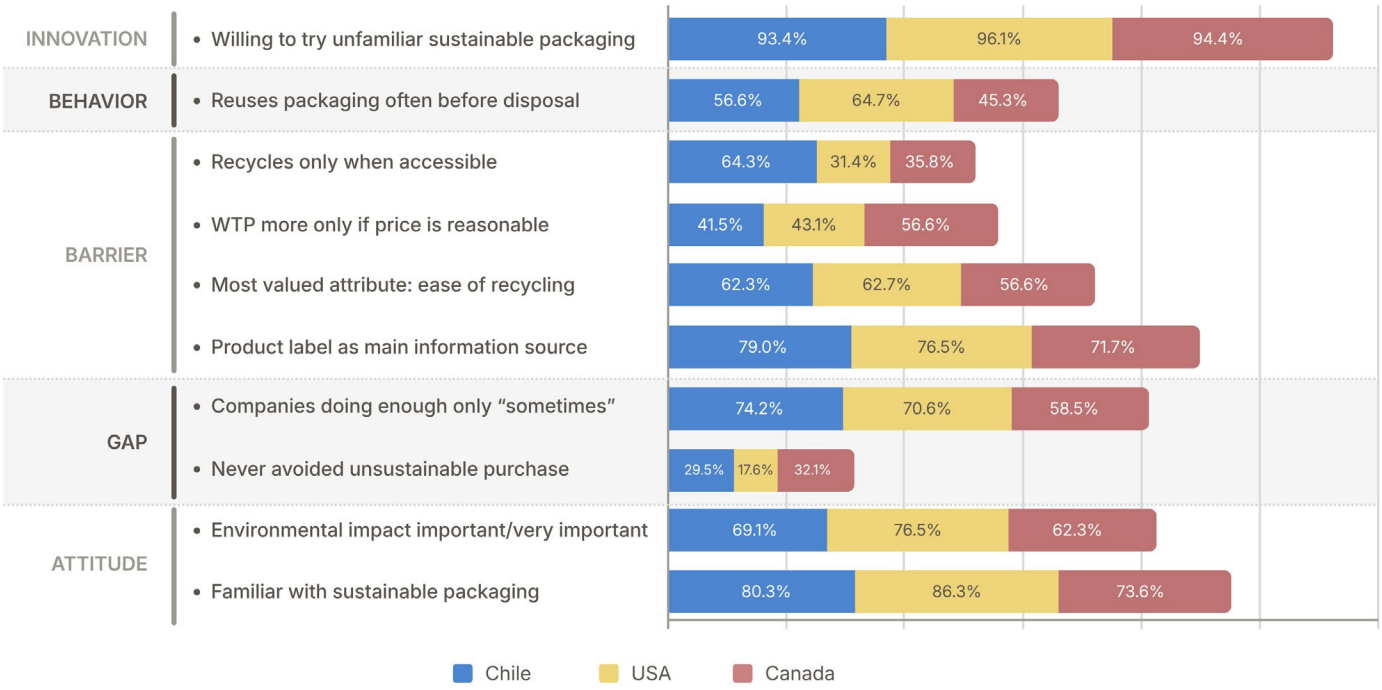


Figure 4. Consumer survey key findings across Chile (n = 530), USA (n = 51), and Canada (n = 53) (ATTITUDE = pro-environmental awareness and preferences; GAP = attitude–behavior discrepancies; BARRIER = structural drivers affecting sustainable packaging adoption; BEHAVIOR = self-reported sustainable practices; INNOVATION = openness to novel sustainable packaging solutions). Source: adapted from thesis results; prepared by the authors.

The data reveal a consistent attitude–behavior gap across all three national samples, accompanied by recurring structural barriers. Despite high levels of familiarity with sustainable packaging (73.6–86.3%), strong environmental concern in purchasing decisions (62.3–76.5%), and widespread willingness to adopt unfamiliar sustainable packaging solutions (93.4–96.1%), consumers across the three countries continue to report behaviors and constraints that limit putting these attitudes into practice. Three findings carry direct design implications for the CSF-SCP. First, label dependency: product labels constitute the primary source of sustainability information for 79.0% of Chilean consumers and more than 70% of respondents in both North American samples. This elevates the Communication/Perceived Quality biomimetic dimension to a core functional requirement. Second, the infrastructure accessibility barrier: 64.3% of Chilean consumers and approximately one-third of North American respondents participate in recycling primarily when collection systems are accessible, highlighting the importance of Material dimension factors that facilitate end-of-life management. Third, openness to innovation: between 93.4% and 96.1% of consumers expressed willingness to try products with unfamiliar yet sustainably promoted packaging materials, suggesting favorable conditions for adopting biomimetic packaging solutions.

4.2.3. Spearman's Correlation Analysis

Table 5 presents all Spearman's correlation coefficients computed between demographic variables and sustainability-related behaviors in the Chilean sample (n = 530), including both significant and non-significant results. These findings complement descriptive gap data by identifying statistical associations between demographic characteristics and packaging sustainability behaviors. A total of 36 correlations were computed (12

survey items × 3 demographic variables). Given the number of simultaneous comparisons, a Bonferroni-corrected significance threshold would be $p < 0.0014$ (0.05/36); under this criterion, only correlations at $p < 0.001$ retain strict significance. Correlations at $p < 0.01$ and $p < 0.05$ are reported for completeness but should be interpreted as suggestive associations rather than confirmatory findings. All results are cross-sectional and describe statistical associations, not causal relationships.

Table 5. Spearman's correlation coefficients between demographic characteristics and sustainability-related perceptions and behaviors in the Chilean sample ($n = 530$). All 36 correlations computed (12 items × 3 variables); non-significant results shown as n.s. Under Bonferroni correction ($\alpha = 0.0014$), only *** retain strict significance. Source: Prepared by the authors.

Survey Item	Age (rho)	Gender (rho)	Education (rho)	Interpretation
Environmental impact on purchase decision	+0.197 ***	−0.131 **	−0.151 ***	Environmental concern varies across demographic groups, and is higher among older respondents and women.
Willingness to pay more for sustainable packaging	+0.115 **	n.s.	n.s.	Older consumers show slightly greater willingness to pay a premium for sustainable packaging.
Packaging material influences the purchase decision	+0.182 ***	−0.128 **	n.s.	Older consumers and women place greater importance on packaging materials during purchasing decisions.
Packaging classification before recycling	+0.097 *	n.s.	+0.103 *	Older and more educated consumers report slightly higher engagement in packaging classification behaviors.
Familiarity with the circular economy	n.s.	n.s.	+0.227 ***	Higher educational attainment is associated with greater familiarity with circular economy concepts.
Source of information about sustainable packaging	n.s.	n.s.	−0.121 **	Sustainability information-seeking behavior varies by educational level.
Willingness to try unfamiliar sustainable packaging	n.s.	−0.090 *	+0.087 *	Openness to novel sustainable packaging solutions varies slightly by gender and education.

*** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$; n.s. = not significant. Spearman's correlation coefficients (rho). Gender coded: 1 = female, 2 = male; negative rho indicates stronger association in female respondents. Total correlations tested: 36 (12 items × 3 demographic variables). Under Bonferroni correction ($\alpha = 0.0014$), only *** results retain strict significance; ** and * results are suggestive associations. All results are cross-sectional. Source: Prepared by authors.

Age was positively associated with the importance attributed to the environmental impact of packaging in purchasing decisions ($\varrho = 0.197$, $p < 0.001$), willingness to pay more for sustainable packaging ($\varrho = 0.115$, $p < 0.01$), and the influence of packaging materials on product selection ($\varrho = 0.182$, $p < 0.001$). Older consumers also reported slightly greater engagement in packaging classification before recycling ($\varrho = 0.097$, $p < 0.05$).

Gender differences were observed in environmental attitudes and innovation-related perceptions. Female respondents attributed greater importance to environmental impacts

($\varrho = -0.131$, $p < 0.01$), reported stronger consideration of packaging materials during purchasing decisions ($\varrho = -0.128$, $p < 0.01$), and showed slightly greater willingness to adopt unfamiliar sustainable packaging solutions ($\varrho = -0.090$, $p < 0.05$).

Educational levels were positively associated with familiarity with the circular economy concept ($\varrho = 0.227$, $p < 0.001$) and engagement in packaging classification behaviors ($\varrho = 0.103$, $p < 0.05$). Conversely, education was negatively associated with the importance attributed to environmental impacts ($\varrho = -0.151$, $p < 0.001$) and reliance on information sources about sustainable packaging ($\varrho = -0.121$, $p < 0.01$), suggesting differences in how sustainability information is processed across educational groups.

Overall, the results indicate that sustainability-related perceptions and behaviors are not homogeneous across consumers. Instead, demographic characteristics appear to influence both the interpretation of sustainability information and the adoption of environmentally responsible packaging practices. These findings reinforce the need for the CSF-SCP to accommodate diverse consumer profiles when translating biomimetic principles into sustainable packaging solutions.

4.2.4. Cross-Cultural Comparative Findings

Given the substantially different sample sizes (Chile $n = 530$ vs. USA $n = 51$; Canada $n = 53$) and the use of snowball sampling in all three countries, the cross-national data do not support inferential comparisons between countries. The following findings from the USA and Canada comparison groups are presented as exploratory context for the Chilean results, not as evidence of universal cross-cultural patterns. Chilean respondents reported greater familiarity with circular economy concepts (66.6%) than participants from the USA and Canada, suggesting higher public awareness within the Chilean sample, likely reflecting the impact of national environmental legislation (Ley REP 20.920; Ley 21.100).

At the same time, structural barriers appeared consistently across countries. Recycling participation remained influenced by accessibility conditions, and willingness to pay more for sustainable packaging was frequently conditional on price considerations. These findings indicate that positive sustainability attitudes do not automatically translate into sustainable consumer behaviors. Future research with probability samples and larger, balanced international cohorts is needed to assess the generalizability of the observed attitude–behavior gap across countries.

Across all three countries, responsibility for packaging sustainability was most frequently attributed to a shared effort involving producers, governments, and consumers. This pattern supports a systemic understanding of packaging sustainability and aligns with circular economy perspectives that emphasize coordinated action among multiple stakeholders rather than individual consumer responsibility alone [39].

4.3. Commercial Packaging Field Study

The field study confirmed the predominance of non-circular packaging in commercial environments. Table 6 summarizes the principal typological and sustainability findings from field observations across the Biobío region's retail landscape.

Table 6. Commercial packaging field study: principal findings from retail observation in the Biobío region, Chile, with design implications and CSF-SCP subsystem assignments. Source: Prepared by the authors.

Finding	Observation	Design Implication	CSF-SCP Subsystem
Dominant material: mixed-material laminates	The majority of observed packaging is non-recyclable under the current infrastructure	Monomaterial design as a priority: Material dimension factor	Functional
Monomaterial packaging concentration	Significantly higher in premium-market products	Sustainability-as-differentiator currently restricts circular packaging to higher-income consumers	Ergonomic/Functional
Biomimetic design elements observed	Present primarily at the formal and communicational level (natural forms, textures, color palettes)	Deep-level biomimetic strategies (structural optimization, biodegradability, adaptive mechanisms) are absent from the commercial landscape	Formal/Functional
Sorting and disposal guidance	Inconsistent or absent across most observed packaging	Communication/Perceived Quality dimension: intuitive disposal cues must be included in the packaging shape and material	Ergonomic
Bio-based/biodegradable packaging	Marginal presence; concentrated in specialty and organic retail	Material dimension factors: significant design opportunity in the mainstream market	Functional

4.4. The Concurrent Systemic Framework for Sustainable Circular Packaging (CSF-SCP)

4.4.1. Model Architecture

The CSF-SCP integrates biomimetic factors, sustainability variables, and circular-economy criteria into a concurrent, systemic design architecture. Figure 5 presents the model's full architecture, showing the entry variables, the three concurrent subsystems, the cross-sectional circular economy criteria, and the output variables.

The model operates at two structural levels. The external system represents the design context: market demands, evidence of consumer behavior (Section 4.2, Tables 4 and 5, Figure 5), regulatory frameworks, sustainability imperatives, and the validated biomimetic factor library (Table 3). The reference system comprises three concurrently operating design subsystems:

- Functional Subsystem: Governs material selection, manufacturing processes, structural performance, and lifecycle technical requirements. Primary biomimetic factor dimensions: Material, Structure/Construction, Processes/Adaptability/Symbiosis, and Function/Strategy/Mechanisms (Table 3).
- Ergonomic Subsystem: Governs user interaction, handling, opening/closing mechanisms, accessibility, and ease of disposal. Consumer survey evidence (Table 5, Figure 4) is operationalized here as an empirical constraint: packaging must communicate its disposal pathway through design properties, form, material texture, and color, without relying on text-based instruction (consistent with [30,40]).
- Formal Subsystem: Governs aesthetic form, morphological language, surface properties, and the experiential relationship between form of packaging and consumer perception. Primary biomimetic factor dimensions: Form/Morphology,

Geometry/Order/Organization, and Communication/Perceived Quality. Research showing that biomimetic aesthetic experience mediates sustainable packaging adoption [26] provides empirical grounding for this subsystem as a functional, not merely decorative, requirement.

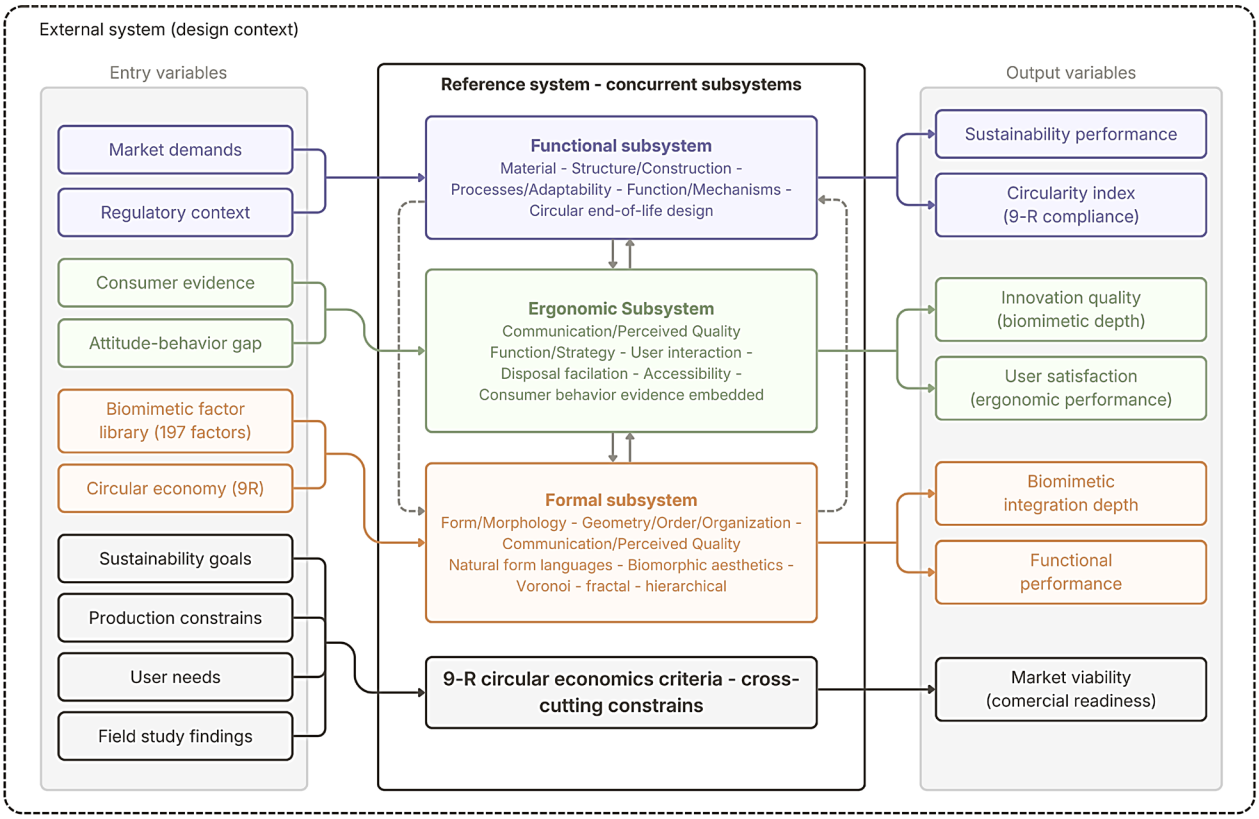


Figure 5. The Concurrent Systemic Framework for Sustainable Circular Packaging (CSF-SCP): entry variables; three concurrent subsystems, each activated by specific biomimetic factor dimensions; cross-sectional circular economy criteria (9-R hierarchy); and output performance variables. Source: own elaboration.

4.4.2. Concurrent Operation and Circular Economy Integration

The critical feature that distinguishes the CSF-SCP from sequential design frameworks is the concurrent, iterative interdependence among the three subsystems. A material decision in the Functional subsystem (e.g., mycelium composite) generates constraints of achievable structural forms in the Formal subsystem. It imposes specific end-of-life communication requirements in the Ergonomic subsystem. A geometric decision in the Formal subsystem (e.g., a Voronoi surface pattern for structural efficiency) constrains material-processing options in the Functional subsystem. It requires an ergonomic evaluation of surface tactility and safety. This interdependence is the generative mechanism through which solutions emerge that are simultaneously technically robust, user-friendly, formally innovative, and ecologically responsible.

Circular economy criteria following the nine-R hierarchy [39] are integrated as cross-sectional constraints across all three subsystems. Design decisions allowing for higher-order circular strategies (refuse unnecessary packaging, reduce material use, allow for reuse) are prioritized over lower-order strategies (recycling, energy recovery). The field study findings (Table 6) and consumer survey evidence (Table 4, Figure 4) are jointly operationalized here: packaging must be designed for domestic end-of-life management to address the infrastructure accessibility barrier identified as a primary structural driver of the attitude–behavior gap.

4.5. Cross-Case Analysis and Applicability Demonstration

Cross-Case Factor Activation and Applicability Assessment

The following cross-case analysis demonstrates applicability of the CSF-SCP's dimensional structure; it does not constitute experimental validation of framework performance in design practice. See Section 5.4 for limitations and future research directions. Table 2 presents the factor-dimension activation matrix across the five analyzed biomimetic cases, with the biological strategies identified for each active dimension. Figure 6 provides the same data as an interactive heatmap, allowing for comparison between cases and dimensions.

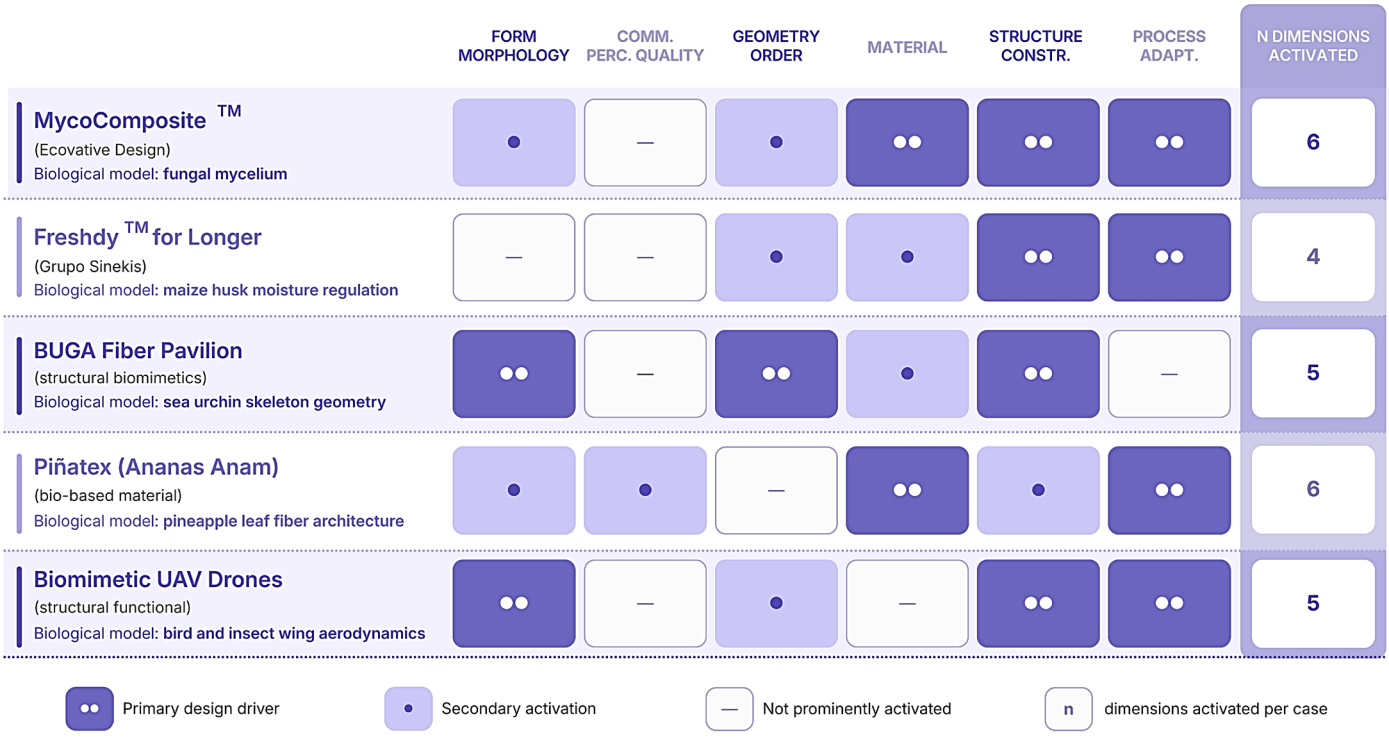


Figure 6. CSF-SCP factor dimension activation heatmap across five biomimetic case studies. Source: authors' own elaboration.

All five cases activated at least five CSF-SCP dimensions as primary or secondary design drivers; no case employed biomimetic strategies that fell outside the model's dimensional framework. The cases with the most direct packaging relevance (MycoComposite™, Piñatex) each activated six of seven dimensions. A key finding is that MycoComposite™ directly addresses the infrastructure accessibility barrier identified in Figure 4 by enabling domestic composting, eliminating reliance on specialist collection infrastructure. This alignment between biomimetic design logic and consumer behavior evidence is precisely the integration mechanism the CSF-SCP is designed to facilitate.

5. Discussion

5.1. The CSF-SCP's Distinctive Contribution

The CSF-SCP addresses a gap confirmed at multiple levels (Figure 1, Table 1). Biomimetic design research has documented individual biological strategies for packaging [5,6,8,10,12] but has not produced operational design frameworks. Circular packaging design research has proposed guidelines and material selection frameworks [2,24] but has not integrated biomimetics. Concurrent systemic design research has developed powerful methodological architecture [21,22] but has not applied it to biomimetic sustainable

packaging. By integrating all three with empirical consumer behavior evidence, the CSF-SCP represents a qualitatively different kind of contribution from its precursors. The cross-case analysis in Section 4.5 constitutes an applicability demonstration, showing that the framework's dimensional structure covers real-world biomimetic design practice, rather than an experimental validation of design performance outcomes.

A central contribution of this research lies not only in the CSF-SCP's development, but also in the construction and content validation of the 197-factor, seven-dimension biomimetic catalog (Table 3). Unlike existing classifications that primarily organize concepts descriptively, the proposed catalog emerged through a triangulated process involving systematic literature review, expert assessment, consumer evidence, and empirical verification through real-world biomimetic case studies. This approach strengthened the conceptual robustness and practical relevance of the resulting framework.

The catalog therefore functions as more than a taxonomy of biomimetic concepts. Its dimensions map directly onto the model's concurrent subsystems (Figure 3), allowing designers to move from biological inspiration to design decisions within a structured, operational framework. In this sense, the catalog serves as a bridge between biomimetic knowledge and design practice.

The cross-case applicability results (Table 2, Figure 6) further support the comprehensiveness of the dimensional architecture. All five biomimetic case studies were successfully interpreted within the proposed framework, with the most comprehensive cases activating six of the seven dimensions. Importantly, no relevant biomimetic strategy identified in the analyzed cases fell outside the framework boundaries, suggesting that the proposed dimensional structure provides broad coverage of current biomimetic design practice.

Taken together, these findings suggest that the contribution of the CSF-SCP extends beyond the proposal of a new design model. The framework provides a structured mechanism for organizing, content-validating, and operationalizing biomimetic knowledge within sustainable packaging design, addressing a methodological gap that has remained largely unresolved in previous research.

5.2. Consumer Evidence as Operative Design Requirements

The translation of evidence on consumer behavior (Table 5, Figure 4) into operational design requirements is a methodological contribution that distinguishes the CSF-SCP from purely theoretical biomimetic frameworks. The finding that recycling participation is primarily infrastructure-constrained rather than motivation-constrained argues for prioritizing Material-dimension factors that enable domestic end-of-life management. The Spearman's correlation analysis (Table 5) adds a demographic dimension: older consumers place significantly greater weight on packaging material in purchase decisions (rho = +0.182, $p < 0.001$), suggesting that the Material dimension biomimetic factors have differential communication value across age groups, a design variable the Ergonomic subsystem must accommodate.

The finding that biomimetic aesthetic experience affects sustainable packaging adoption [26] provides direct empirical support for the CSF-SCP's concurrent Formal subsystem as a functional, not merely aesthetic, requirement. When packaging communicates biomimetic design rationale through form and material, it addresses the information deficit barrier identified in Figure 4 without relying on text-based instruction, precisely the design strategy that Cook et al. [30] and Norton et al. [40] identified as most effective.

5.3. Biomimetics as Inherently Circular

A recurring finding across the theoretical review, empirical evidence (Table 6), and case analyses (Table 2) is the natural structural alignment between biomimetic design

principles and circular economy imperatives. The cases that most activate the CSF-SCP's dimensions (MycoComposite™, Freshdy™, Piñatex) also achieve the highest circular economy performance, not as add-on features but as direct consequences of their biomimetic functional logic. This confirms the theoretical argument of Al Haj Eid et al. [41] with empirical evidence from design practice: biomimetics and the circular economy are structurally aligned because biological systems are the only known complex material systems to have achieved genuine long-term circularity at scale.

5.4. Limitations and Future Research

Several limitations warrant acknowledgment. The consumer survey employed snowball sampling, likely overrepresenting sustainability-literate, higher-education respondents; the North American group (n = 104) is small, limiting the statistical power for cross-cultural comparisons. The model's validation is currently theoretical-analytical and case-based rather than experimental; structured design exercises and industry project deployment with empirical performance measurement are needed. The biomimetic factor catalog will require updating as new research areas emerge, particularly in synthetic biology, nanotechnology, and computational material design. Priority lines for future research include: (a) computational implementation and AI-assisted biological database integration [17]; (b) experimental validation in real design projects; (c) extension to other product categories; and (d) development of standardized biomimetic packaging assessment protocols to support regulatory certification. The cross-case applicability assessment was coded primarily by a single researcher; while a partial second review was conducted for three cases with no substantive disagreements, the absence of full dual coding and a formal inter-coder agreement measure is acknowledged as a methodological limitation. Future applicability assessments should include independent dual coding and inter-coder reliability measures.

5.5. Policy Implications

The CSF-SCP's empirical findings carry direct implications for packaging sustainability policy at national and supranational levels. The consumer survey evidence, specifically the finding that 64.3% of Chilean consumers recycle only when infrastructure is convenient and that 79% rely exclusively on product labels as their primary sustainability information source, argues for regulatory frameworks that mandate communication of disposal pathways through packaging design properties rather than text-based labeling alone. This design-embedded communication strategy is consistent with the EU Packaging and Packaging Waste Regulation (PPWR, 2024) requirement for intuitive sorting guidance, Chile's Extended Producer Responsibility Law (Ley REP 20.920), and the No More Bags Act (Ley 21.100): all three frameworks signal that consumers cannot be relied upon to seek out sustainability information, and that packaging must therefore communicate its end-of-life pathway through intrinsic design properties.

At the design policy level, the CSF-SCP operationalizes a principle confirmed by the European Commission and multiple systematic reviews: the design stage determines approximately 80% of a product's environmental impact [2,3]. Current packaging design practice in commercial environments, as documented in the field study (Table 6), shows that this principle is not yet applied systematically. Integrating the CSF-SCP's seven-dimension nature-inspired factor catalog into design education curricula, professional certification standards for packaging designers, and regulatory eco-design guidelines would provide the upstream design infrastructure needed to translate the 80% principle into practice at scale. The cross-national consistency of the attitude–behavior gap (Chile, USA, Canada; n = 634) suggests that such policy interventions are not culturally specific but

represent a structural feature of sustainable packaging markets that requires design-level, not merely behavioral or infrastructural, solutions.

6. Conclusions

This paper presented the Concurrent Systemic Framework for Sustainable Circular Packaging (CSF-SCP) as a methodological framework that, for the first time, integrates a rigorously validated biomimetic factor catalog, empirical evidence of consumer behavior, and a concurrent systemic design architecture into an operational tool for sustainable packaging design. The following conclusions are drawn:

(1) The 197-factor, seven-dimension CSF-SCP catalog (Table 3) represents the most comprehensive content-validated classification of biomimetic design resources applicable to packaging. By systematically identifying factors from 68 publications and validating them through 11 international experts (Figure 2; Table 4), the framework operationalizes the full design-relevant scope of biological strategies into a directly usable reference for packaging designers.

(2) Consumer behavior evidence (Tables 4 and 5; Figure 3) reveals that the attitude–behavior gap is structurally driven and carries direct, specific design implications. Infrastructure accessibility barriers and information shortcomings, not attitudinal deficiency, are the primary constraints of sustainable packaging behavior across three countries (n = 634). This elevates the Communication/Perceived Quality dimension and domestic end-of-life performance factors to core functional requirements of any sustainable packaging design.

(3) The concurrent systemic architecture (Figure 4) allows biomimetic factors to become operative design variables rather than isolated inspirations. By embedding the factor catalog (Table 3) within simultaneous, interdependent Functional, Ergonomic, and Formal subsystems, the CSF-SCP ensures that biomimetic strategies are integrated across the full complexity of packaging design. Field study evidence (Table 6) confirms that current commercial practice activates biomimetic strategies primarily at the formal level, with deep-level integration remaining an open design opportunity.

(4) In terms of the United Nations Sustainable Development Goals, the CSF-SCP contributes operationally to SDG 12 (Responsible Consumption and Production: through upstream circular packaging design that embeds end-of-life circularity as a core design requirement rather than a downstream consideration), SDG 13 (Climate Action: through material efficiency, domestic biodegradability, and reduced-infrastructure end-of-life management enabled by the model's Material and Processes dimensions), and SDG 17 (Partnerships for the Goals: through the multi-stakeholder integration, designer, consumer, regulator, that the concurrent three-subsystem architecture enables, ensuring that design decisions reflect producer, user, and policy perspectives simultaneously). These alignments position the CSF-SCP not only as a disciplinary contribution to packaging design methodology, but also as a practical instrument for the sustainable development transition in the global packaging sector.

(5) Cross-case analysis (Table 2; Figure 6) demonstrates dimensional coverage and cross-case applicability. All five analyzed biomimetic design cases activated at least four CSF-SCP dimensions, and none employed strategies that fell outside the model's framework. Cases with the highest packaging relevance (MycoComposite™, Piñatex) activated six of seven dimensions, demonstrating that comprehensive sustainable packaging solutions benefit from multi-dimensional biomimetic integration of precisely the type the CSF-SCP is designed to facilitate. It is noted that this cross-case analysis demonstrates applicability of the framework's dimensional structure; experimental validation in live design projects remains a priority direction for future research (Section 5.4).

https://doi.org/10.3390/su182111224

The CSF-SCP is positioned as a contribution to sustainable product design, biomimetic design methodology, and circular packaging research. Priority directions for future research include: (a) experimental validation in real design projects—structured design exercises in which packaging designers use the CSF-SCP and outcomes are compared with designs developed without the framework or with an alternative existing methodology; (b) computational implementation and AI-assisted biological database integration; (c) extension to other product categories; and (d) development of standardized biomimetic packaging assessment protocols to support regulatory certification.

Author Contributions: Conceptualization, A.P.L.V. and B.H.O.; Methodology, A.P.L.V., J.C.B.W. and B.H.O.; Software, A.P.L.V.; Validation, A.P.L.V., J.C.B.W. and M.L.B.; Formal analysis, A.P.L.V. and M.L.B.; Investigation, A.P.L.V.; Resources, B.H.O.; Data curation, A.P.L.V. and M.L.B.; Writing—original draft, A.P.L.V.; Writing—review & editing, A.P.L.V., J.C.B.W. and M.L.B.; Visualization, M.L.B.; Supervision, J.C.B.W. and B.H.O.; Project administration, A.P.L.V.; Funding acquisition, A.P.L.V. All other authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Academic Improvement Program of the University of Bío-Bío, Concepción, Chile.

Institutional Review Board Statement: Ethical review and approval were waived for this study by the ethical guidelines of Universidad Técnica Federico Santa María (Chile) (Approval Report Code No. 0013/2026) for non-clinical research with human participants. The committee concluded that the project met the required ethical standards and complied with applicable national regulations, including Chilean Law No. 19,628 on the Protection of Private Life and Personal Data (Ley 19.628 sobre Protección de la Vida Privada y sus modificaciones). Informed consent was obtained from all participants prior to data collection. Participant data were anonymized and stored securely in accordance with Law No. 19,628. Under the applicable Chilean and Spanish national regulations, formal IRB or ethics committee approval was not required for the non-clinical, non-sensitive, voluntary adult survey/interview components without deception or risk of harm.

Informed Consent Statement: Informed consent was obtained from all subjects involved in this study.

Data Availability Statement: The validated biomimetic factor catalog (197 factors, seven dimensions) and aggregate consumer survey data are available from the corresponding author upon reasonable request.

Acknowledgments: During the preparation of this manuscript/study, the author(s) used Claude, Anthropic, for the purpose of development of draft visual representations of figures. The authors have reviewed and edited the output and take full responsibility for the content of this publication.

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

References

1. World Economic Forum; Ellen MacArthur Foundation; McKinsey & Company. The New Plastics Economy: Rethinking the Future of Plastics. 2016. Available online: https://www.ellenmacarthurfoundation.org/the-new-plastics-economy-rethinking-the-future-of-plastics (accessed on 7 April 2026).
2. Zhu, Z.; Liu, W.; Ye, S.; Batista, L. Packaging design for the circular economy: A systematic review. *Sustain. Prod. Consum.* **2022**, *32*, 817–832. https://doi.org/10.1016/j.spc.2022.06.005.
3. Pathan, R.K.; Aurisicchio, M. Design framework for circular and sustainable packaging design. *Proc. Des. Soc. USA* **2025**, *5*, 1175–1184. https://doi.org/10.1017/pds.2025.10131.
4. Tarantino, M.; Mosconi, E.M.; Tola, F.; Gianvincenzi, M.; Delussu, A.M. A Comprehensive and Multidisciplinary Framework for Advancing Circular Economy Practices in the Packaging Sector: A Systematic Literature Review on Critical Factors. *Sustainability* **2026**, *18*, 192. https://doi.org/10.3390/su18010192.

5. Benyus, J.M. *Biomimicry: Innovation Inspired by Nature*; William Morrow: New York, NY, USA,1997.
6. Michael, P. *Biomimicry in Architecture*; RIBA Publishing, London, UK, 2019.
7. Xiao, C.; Seong, D. Research on the Application of Biomimetic Design in Art and Design. *Biomimetics* **2025**, *10*, 541. https://doi.org/10.3390/biomimetics10080541.
8. Ilieva, L.; Ursano, I.; Traista, L.; Hoffmann, B.; Dahy, H. Biomimicry as a Sustainable Design Methodology, Introducing the 'Biomimicry for Sustainability' Framework. *Biomimetics* **2022**, *7*, 37. https://doi.org/10.3390/biomimetics7020037.
9. Jones, M.; Mautner, A.; Luenco, S.; Bismarck, A.; John, S. Engineered mycelium composite construction materials from fungal biorefineries: A critical review. *Mater. Des.* **2020**, *187*, 108397. https://doi.org/10.1016/j.matdes.2019.108397.
10. Dhatt, P.S.; Hu, A.; Hu, C.; Huynh, V.; Dai, S.Y.; Yuan, J.S. Biomimetic layered, ecological, advanced, multi-functional film for sustainable packaging. *Nat. Commun.* **2025**, *16*, 6649. https://doi.org/10.1038/s41467-025-61693-2.
11. Wegst, U.G.K.; Bai, H.; Saiz, E.; Tomsia, A.P.; Ritchie, R.O. Bioinspired structural materials. *Nat. Mater.* **2015**, *14*, 23–36. https://doi.org/10.1038/nmat4089.
12. Liu, G.; Min, T.; Li, X.; Zhao, Y.; Li, Z.; Liu, J.; Wen, Y. Biomimetic functional food packaging materials. *Chem. Eng. J.* **2024**, *499*, 156146. https://doi.org/10.1016/j.cej.2024.156146.
13. Linder, B.; Huang, J. A Design Process Framework and Tools for Teaching and Practicing Biomimicry. *Biomimetics* **2025**, *10*, 376. https://doi.org/10.3390/biomimetics10060376.
14. Alemzadeh, K. Innovative Bionics Product Life-Cycle Management Methodology Framework with Built-In Reverse Biomimetics: From Inception to Clinical Validation. *Biomimetics* **2025**, *10*, 158. https://doi.org/10.3390/biomimetics10030158.
15. Goyes-Balladares, A.; Moya-Jiménez, R.; Molina-Dueñas, V.; Chaca-Espinoza, W.; Magal-Royo, T. What Inspires Biomimicry in Construction? Patterns, Trends, and Applications. *Biomimetics* **2025**, *10*, 259. https://doi.org/10.3390/biomimetics10050259.
16. Gerola, A.; Robaey, Z.; Blok, V. What Does it Mean to Mimic Nature? A Typology for Biomimetic Design. *Philos. Technol.* **2023**, *36*, 65. https://doi.org/10.1007/s13347-023-00665-0.
17. Marques de Sá, A.A.; Aoussat, A.; Maranzana, N. A Comparative Study on the Use of Artificial Intelligence and Other Approaches for Biomimetic Design: Application in Packaging Innovation for Fragile Products. In *Product Lifecycle Management. Integrating Digital Technologies for Sustainability and Innovation*; Sureephong, P., Danjou, C., Bouras, A., Eds.; PLM 2024. IFIP Advances in Information and Communication Technology; Springer: Cham, Switzerland, 2025; Volume 740. https://doi.org/10.1007/978-3-031-93319-6_22.
18. Kozik-Kołodziej, N. Consumer Attitudes and Perceptions Toward Sustainable Packaging: A Systematic Literature Review. *Sustainability* **2026**, *18*, 1235. https://doi.org/10.3390/su18031235.
19. Sharma, A.P. Consumers' purchase behaviour and green marketing: A synthesis, review and agenda. *Int. J. Consum. Stud.* **2021**, *45*, 1217–1238. https://doi.org/10.1111/ijcs.12722.
20. Selvaggi, R.; Reitano, M.; Lombardo, S.; Pappalardo, G. Shaping "green" choices: The role of information, product appearance and environmental attitudes in consumers' willingness to pay for sustainable food packaging. *J. Environ. Manag.* **2026**, *401*, 128886. https://doi.org/10.1016/j.jenvman.2026.128886.
21. Hernandis, B. Desarrollo de una Metodología Sistémica Para el Diseño de Productos Industriales. Ph.D. Thesis, Universitat Politècnica de València, Valencia, Spain, 2004.
22. Hernandis-Ortuño, B.; Agustín-Fonfría, M.A.; Iñaki, F.; Esnal-Angulo, I. *EcoDiseño Concurrente*; Red Internacional de Investigación en Diseño Sistémico (RDIS): Valencia, Spain, 2019.
23. Fang, Y.; Qu, Y. Symmetric Alignment Between Affective Semantics and Biomimetic Forms: Sustainable Packaging Design and Decision Support. *Symmetry* **2026**, *18*, 19. https://doi.org/10.3390/sym18010019.
24. Markevičiūtė, Z.; Varžinskas, V. Smart Material Choice: The Importance of Circular Design Strategy Applications for Bio-Based Food Packaging Preproduction and End-of-Life Life Cycle Stages. *Sustainability* **2022**, *14*, 6366. https://doi.org/10.3390/su14106366.
25. Monteiro, M.G.V.; Melo, A.C.S.; Junior, A.E.B. A review of design guidelines for packaging circularity. In *ENSUS 2025—XIII Encontro de Sustentabilidade em Projeto*; Virtuhab: Florianópolis, Brazil, 2025; pp. 1339–1351. Available online: https://repositorio.ufsc.br/handle/123456789/266955 (accessed on 28 June 2026).
26. Luo, T.; Tu, J.; Liu, L.; Miao, Y.; Liu, T. Youth green aesthetic perception and psychological influence on the adoption of sustainable packaging for biomimetic cultural products in social media environments. *Front. Psychol.* **2026**, *17*, 1752048. https://doi.org/10.3389/fpsyg.2026.1752048.
27. Lisboa, A.; Vitorino, L.; Antunes, R. Gen Zers' intention to purchase products with sustainable packaging: An alternative perspective to the attitude-behaviour gap. *J. Mark. Manag.* **2022**, *38*, 967–992. https://doi.org/10.1080/0267257X.2022.2083214.

28. Wagermaier, W.; Razghandi, K.; Fratzl, P. A Bio-Inspired Perspective on Materials Sustainability. *Adv. Mater.* **2025**, *37*, 2413096. https://doi.org/10.1002/adma.202413096.
29. Versino, F.; Ortega, F.; Monroy, Y.; Rivero, S.; López, O.V.; García, M.A. Sustainable and Bio-Based Food Packaging: A Review on Past and Current Design Innovations. *Foods* **2023**, *12*, 1057. https://doi.org/10.3390/foods12051057.
30. Cook, B.; Costa Leite, J.; Rayner, M.; Stoffel, S.; van Rijn, E.; Wollgast, J. Consumer Interaction with Sustainability Labelling on Food Products: A Narrative Literature Review. *Nutrients* **2023**, *15*, 3837. https://doi.org/10.3390/nu15173837.
31. Briede-Westermeyer, J.C.; Cabello-Mora, M.; Hernandis-Ortuño, B. Concurrent sketching model for the industrial product conceptual design. *Dyna* **2014**, *81*, 199–208. https://doi.org/10.15446/dyna.v81n187.41068.
32. Rivera, J. Herramientas para el Desarrollo de Productos Sostenibles. Ph.D. Thesis, Universitat Politècnica de València, Valencia, Spain, 2018.
33. Lynn, M.R. Determination and quantification of content validity. *Nurs. Res.* **1986**, *35*, 382–385. https://doi.org/10.1097/00006199-198611000-00017.
34. Herrmann, C.; Rhein, S.; Sträter, K.F. Consumers' sustainability-related perception of and willingness-to-pay for food packaging alternatives. *Resour. Conserv. Recycl.* **2022**, *181*, 106219. https://doi.org/10.1016/j.resconrec.2022.106219.
35. Yin, R.K. *Case Study Research and Applications: Design and Methods*, 6th ed.; SAGE Publications: Thousand Oaks, CA, USA, 2018.
36. Instituto Nacional de Estadísticas (INE). *Encuesta de Presupuestos Familiares 2021–2022*; INE: Santiago, Chile, 2022. Available online: https://www.ine.gob.cl/estadisticas/sociales/ingresos-y-gastos/encuesta-de-presupuestos-familiares (accessed on 25 August 2026).
37. Zsóka, Á.; Szerényi, Z.M.; Széchy, A.; Kocsis, T. Greening due to environmental education? Environmental knowledge, attitudes, consumer behavior and everyday pro-environmental activities of Hungarian high school and university students. *J. Clean Prod.* **2013**, *48*, 126–138. https://doi.org/10.1016/j.jclepro.2012.11.030.
38. Petkowicz, A.; Pelegrini, T.; Bodah, B.W.; Rotini, C.D.; Moro, L.D.; Neckel, A.; Spanhol, C.P.; Araújo, E.G.; Pauli, J.; Mores, G.d.V. Purchasing Intention of Products with Sustainable Packaging. *Sustainability* **2024**, *16*, 2914. https://doi.org/10.3390/su16072914.
39. Potting, J.; Hekkert, M.; Worrell, E.; Hanemaaijer, A. *Circular Economy: Measuring Innovation in the Product Chain*; PBL Netherlands Assessment Agency: The Hague, The Netherlands, 2017.
40. Norton, V.; Waters, C.; Oloyede, O.O.; Lignou, S. Exploring Consumers' Understanding and Perception of Sustainable Food Packaging in the UK. *Foods* **2022**, *11*, 3424. https://doi.org/10.3390/foods11213424.
41. Eid, M.A.H.; Al-Abdallah, G. Sustainable development through biomimicry: Enhancing circular economy practices for environmental sustainability. *Sustain. Dev.* **2024**, *32*, 6045–6056. https://doi.org/10.1002/sd.3010.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.