Artículo

Jurui, Cashew Beyond Nut and Shell: Weaving Material Relations Across People, Place, and Culture.

Jurui, marañón mas allá de su nuez y su cascara:
Tejiendo relaciones con la materia las personas, el lugar y la cultura.

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Abstract

This article investigates the cashew nut and its by-products not merely as agricultural resources but as active materials whose relational properties influence both human practices and ecological systems in the Vichada region of Colombia. Employing a material-centred and participatory design methodology that integrates co-design with local communities, laboratory experimentation, and field testing, the project examines the transformation of cashew shells and cashew nutshell liquid into viable materials for sustainable development. The study identifies new applications such as natural coatings, material composites, ergonomic packaging tools, and safety processing machinery, that enhance local processing practices while fostering economic resilience. By situating design as a relational practice that connects material, territory, and culture, this work advances a model of innovation grounded in local knowledge and ecological interdependence.

Resumen

Este artículo investiga el marañón (anacardo) y sus subproductos no solo como recursos agrícolas, sino como materiales activos cuyas propiedades relacionales influyen tanto en las prácticas humanas como en los sistemas ecológicos de la región del Vichada, en Colombia. Mediante una metodología de diseño participativo centrada en el material —que integra el codiseño con comunidades locales, la experimentación en laboratorio y las pruebas de campo—, el proyecto examina la transformación de las cáscaras y el líquido de la nuez de marañón en materiales viables para el desarrollo sostenible. El estudio identifica nuevas aplicaciones, como recubrimientos naturales, compuestos materiales, herramientas ergonómicas para el envasado y maquinaria segura para el procesamiento, que mejoran las prácticas locales de producción al tiempo que fomentan la resiliencia económica. Al situar el diseño como una práctica relacional que conecta material, territorio y cultura, este trabajo propone un modelo de innovación basado en el conocimiento local y la interdependencia ecológica.

Figure 1 (a): The land of the Orinoco River, 2022;
(b): The Vichada region of Colombia within the Orinoco basin in South America.

1. Introduction

The cashew tree (*Anacardium occidentale* L.), commonly known as cashew, is a perennial fruit species of the family Anacardiaceae, native to the tropical regions of South America. Its centre of origin is located in the Brazilian Amazon; however, the fertile soils and favourable climate of adjacent zones, including the savannas of Colombia, Venezuela and the Guianas, have long fostered the presence and natural diversity of this species (de Brito *et al.*, 2018; Orduz-Rodríguez and Rodríguez-Polanco, 2022).

Significant genetic variation of the cashew has been documented in these peripheral areas, particularly in the Llanos region, which extends across the Orinoco basin. This region became increasingly important during the Spanish colonial expansion in the 17th and 18th centuries, as the empire sought to establish vast cattle ranches across South America. The Orinoco River and its surrounding plains served not only as a transportation artery but also as a strategic economic frontier for the Crown. Colonists, missionaries and *encomenderos*[1] introduced cattle and horses that quickly adapted to the open grasslands of the Llanos, which lacked dense forests and provided abundant pastures (Crosby, 2003; Figure 1a).

By the mid-1700s, large-scale cattle ranching had become a dominant land use across the region. This livestock-based economy profoundly shaped the ecological and socio-political landscapes, displacing Indigenous groups and converting previously unmanaged or forested lands into open savannas. It also encouraged the introduction and domestication of various crops, including the cashew tree, which benefitted from disturbed or open soils and co-evolved within these newly anthropised environments.

Thus, the history of the cashew tree's expansion is intertwined with the broader story of colonial land appropriation, the establishment of cattle-based economies, and the ecological

1 *Encomenderos* were Spanish colonists granted the right to extract labor and tribute from Indigenous people under the *encomienda* system, in exchange for offering protection and religious instruction.

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Figure 2 Cashew nut and apple, 2022.

transformation of the Llanos. As a result, regions such as Vichada, Meta, and Apure (once frontiers of Spanish colonial livestock production), became secondary centres of botanical diversity and adaptation for the cashew, where the species acclimatised to local conditions (Figure 1b).

Since its initial domestication, the cashew has been valued for its highly nutritious nut and its pseudo-fruit commonly known as the "cashew apple", which is used in agro-industry and consumed fresh (Figure 2).

In the 16th century, Portuguese explorers introduced the species to India (Goa) and Africa (Mozambique), from where it spread to other regions of East Africa, Southeast Asia and northern Australia. Today, cashew cultivation is widespread across tropical zones around the world, primarily between latitudes 30° north and 30° south (Abdul Salam & Peter, 2010). Countries such as Vietnam, India, Nigeria, Brazil and Ivory Coast lead global production, with Vietnam standing out as the world's largest exporter of cashew nuts (Food and Agriculture Organization, 2021a).

In Colombia, the formal cultivation of cashew began in 1963, sponsored by the Ministry of Agriculture. This initiative emerged in a context where vast areas of Colombian territory, particularly in the Eastern Plains (Llanos Orientales) were predominantly dominated by extensive cattle ranching. Recognising the potential of underutilised land for alternative crops, national institutions promoted cashew as a promising species for agricultural diversification (Gobierno Departamental del Vichada, 2020).

Following the initial efforts, a systematic programme of genetic improvement and technological development was launched. This

Figure 3 Comparative sizes of cashew nuts, 2022.

programme aimed to identify and propagate elite genotypes capable of thriving under the specific climatic conditions of the Altillanura region, which is a vast savanna characterised by acidic, low-fertility soils, high solar radiation, and pronounced dry seasons. As a result, outstanding clones were selected and recommended for commercial cultivation[2] (Clímaco *et al.*, 2016; Figure 3). These genotypes offered not only superior adaptability and yield potential but also a differentiated product for emerging domestic and international markets.

Today, cashew cultivation in Colombia spans multiple regions, from the Llanos Orientales to the dry zones of the Caribbean coast. However, significant disparities remain in terms of technological inputs, land tenure systems and productivity levels. While some plantations employ improved clones and basic post-harvest handling techniques, many rely on low technology and lack access to mechanisation, irrigation and technical assistance. These limitations have constrained the expansion and competitiveness of the region and its inhabitants (Das & Arora, 2017).

Beyond agronomic challenges, cashew production is also hindered by critical health and safety issues, particularly concerning the handling of cashew nutshell liquid (CNSL). This dark, viscous oil, located between the shells of the cashew nut, is highly corrosive and contains compounds such as anacardic acid, cardanol and cardol (Berry & Sargent, 2011). While these phenolic substances are valuable for industrial applications (Patel *et al.*, 2006), they pose serious risks to human health when not managed properly. Exposure to cashew nutshell liquid can cause severe chemical burns, dermatitis and long-term skin damage (Andonaba, 2017).

Moreover, the absence of regional infrastructure, such as paved roads, processing centres, and storage facilities, limits the ability of producers to transport and commercialise their products efficiently. Consequently, despite the crop's potential, economic gains remain modest and unevenly distributed.

2 Clones of the Vichada region known as Mapiria Ao1, Yopare Ao2 and Yucao Ao3.

Cashew cultivation holds significant promise for rural development, particularly in underdeveloped areas, where it is also possible to consider ecological balance. Its resilience to drought, low soil fertility and climatic variability makes it an ideal crop for climate-adapted agriculture. When integrated with sustainable value chains and supported by institutional and technological investments, cashew farming can promote inclusive economic growth, improve livelihoods and foster agro-industrial innovation, aligned with the sustainable developing goals of the United Nations, particularly SDG 1, No Poverty; SDG 3, Good Health and Well-Being and SDG 11, Sustainable Cities and Communities.

In this context, enhancing the value of cashew sub-products represents both a challenge and an opportunity: a way to transition from a raw commodity-based system to an active material whose relational properties could shape both human practices and ecological systems in the Vichada region of Colombia.

This research was born from the intersection of socio-economic marginalisation, underutilised agricultural by-products and environmental vulnerability in the Vichada region. The problem setting emerged from the hazardous and inefficient conditions under which local communities process cashew nuts, exposing themselves to cashew nutshell liquid (CNSL), the environmental burden posed by the massive disposal of cashew shells and the evident limitations that this region has to improve both the productivity of this crop as well as their quality of life. The general objective of the Jurui project is to explore alternative pathways for the valorisation of cashew by-products through material innovation, participatory design and technology development, with a focus on local relevance. Specifically, it seeks to (1) reduce human exposure to CNSL through technological redesign; (2) develop new material applications from cashew waste; and (3) enhance community engagement through co-design processes that strengthen territorial autonomy. The justification lies in the project's capacity to bridge gaps between material science, design and local development, offering a replicable and scalable model for circular innovation that is inclusive, locally grounded and globally relevant.

2. Methodological Blend of an Interdisciplinary Work

The methodology employed in this research combines participatory design (Bratteteig *et al.*, 2012), material-driven experimentation (Karana *et al.*, 2015) and contextual fieldwork (Crang, 2003), blending approaches from design, engineering and the social sciences. Co-creation workshops with local communities formed the foundation for understanding situated knowledge, cultural practices and material relationships surrounding cashew production. These insights were subsequently translated into material explorations through DIY-material approaches (Rognoli *et al.*, 2015), rapid prototyping and expressive–sensory evaluations (Rognoli & Levi, 2005). This process enabled a human–material dialogue that informed the development of both bio-based materials and cashew-processing technologies. Simultaneously, scientific analysis and laboratory validation were carried out in parallel with ethnographic immersion and actor mapping, following the principle of design–build–test–learn (Wheelwright & Clark, 1992). In this iterative approach, what was conceived was continuously refined during testing phases, ensuring that material transformation remained grounded in the lived realities of the region. Rather than applying these methods in a fixed sequence, the project adopted a flexible, iterative structure between co-creation, experimentation and validation. Findings in one domain continuously influenced and reshaped decisions in others, reinforcing the relational and evolving nature of the work.

2.1. Understanding the Cashew from Inside

Understanding the cashew from within goes far beyond analysing the nut's nutritional composition or the mechanics of its shell. It requires a holistic perspective, one that considers the territory where it is grown, the communities that cultivate and process it and the many social, economic and ecological opportunities this fruit can offer. True understanding emerges at the intersection of ecology, economy and environment (Braungart & McDonough, 2002).

Recognising this, the design and engineering team proposed a multidimensional research approach aimed at fostering long-term sustainability. Not only for the cashew value chain, but also for the well-being of the people and ecosystems that depend on it. For many communities, particularly in the Vichada region, the cashew represents more than a crop: it is a livelihood, a cultural reference point and a future possibility.

This project integrates technical knowledge with local wisdom, ensuring that the process of innovation is rooted in the realities and aspirations of the region. The research team has committed to working alongside key local actors (landowners, farmers, agronomists and processors who collect and manually open the nuts), whose contextual expertise is essential for meaningful, sustainable outcomes of these edible and non-edible materials.

Structured around two core lines of action, the project first addresses the development of value-added products derived from cashew processing byproducts, including the shell, oil and nut. Secondly, and just as importantly, it adopts a human-centred approach that values the role of traditional knowledge and manual practices. Instead of replacing these practices with automated techniques that could alienate local communities, the project seeks to strengthen, preserve and evolve them. It seeks to develop a model of innovation that is inclusive, culturally grounded and socially just.

The project begins with a regional exploration. An immersive, co-creative effort involving designers, engineers, cultivators and governmental entities. The goal of these immersion sessions is to enable the research team to recognise itself as part of the territory (Moore & Garzón, 2010). Although not native to the region, the team is native to the country and understands the importance of comprehending the socio-economic dynamics that have led to the region's underdevelopment, as well as the opportunities for sustainable economic, ecological and social growth.

From these early interactions with local growers, a wealth of qualitative data was collected, ranging from insights into lifestyle, traditions, seasonal calendars, work rhythms and expectations surrounding the cashew tree following the methodology of Smith (2008). Colour palettes, symbols, native words, knowledge, sayings, myths and rituals connected to the cashew were gathered and served as essential raw material for the project's conceptualisation. In particular, we drew inspiration from the Sikuani people, who are concentrated mainly in this department, with 61.2% of their population (12,119 people) residing in Vichada. The Sikuani, also known as *kive* (people) or *Guahibo*, speak the Sikuani language, which belongs to the Guahibana linguistic family. Their culture venerates nature, the fruits and crops that come from the Tree of Life, *Kaliawiri* (Pónare González & Pónare, 2015). After several trips, interactions with the people and long hours of travel across the vast plains of the region, the design team proposed naming the project *Jurui*. In the Sikuani language, *Jurui* means *cashew*, though within their culture, they primarily value the pseudo-fruit rather than the nut itself. However, they do recognise the nut as a nutritious element.

The development of the project's visual identity, its image, symbol, and communication language became a fundamental unifying element. This identity enabled the various disciplines involved (chemical engineers, mechanical engineers, biologists, materials scientists, product and graphic designers and innovation managers) to share a common conceptual framework.

The *Jurui* visual concept was shared with the community, facilitating co-creation processes that validated whether the proposed identity was culturally appropriate, aligned with the project's principles, and meaningful as a symbol for the cashew in the Vichada region. After several iterations and refinements, *Jurui* was officially established as a multidimensional research project for the sustainable development of the Vichada region through the processing of the cashew nut and its derivative sub-products (Figure 4).

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Figure 4 Juruy brand development, 2022.

Each project iteration was locally validated with stakeholders across the cashew production chain, ensuring that community expectations and research objectives remained aligned throughout the process. Co-creation workshops served as the project's integrative axis. Over the three-year development period, six workshops were conducted, each focusing on integration and participatory design. These sessions followed creative development methodologies, enabling the team to interact directly with the community and co-construct blended knowledge. The six workshops were proposed as follows:

- Social Cartography (Moore & Garzón, 2010; Figure 5);
- Technological Capabilities (Bell & Pavitt, 1993);
- Scamper (Eberle, 1996; Figure 14);
- Tangible Models;
- Prototyping and Prioritisation (Figure 15);
- Construction and Validation (Stappers, 2007; Stappers *et al.* 2014; Figures 16-18).

These workshops shaped the trajectory of the research activities, contributing critical insights for each alternative use, application and development related to cashew nutshell and its residues.

Through this collaborative process, several potential products and applications emerged from the collective intelligence of the community and the interdisciplinary team. These included: natural waterproofing agents for wooden surfaces and construction materials; flame retardant additives, plasticisers and lubricants derived from transformed cashew nutshell liquid; bio-based composite materials for the local manufacturing of crates, baskets and transport containers, aimed at reducing dependency on imported plastics; machinery for cashew nut processing, designed to improve safety and well-being for local processors; and a sustainable economic model for the region to implement across the entire cashew production chain in the medium term.

The workshops also fostered new relational understandings of the cashew nut beyond its economic value as a cultural, ecological and material agent. As these ideas took shape, they informed iterative refinements of both material explorations and territorial strategies, ensuring that the diverse outcomes of the research remained meaningfully embedded within the rhythms and realities of life in Vichada.

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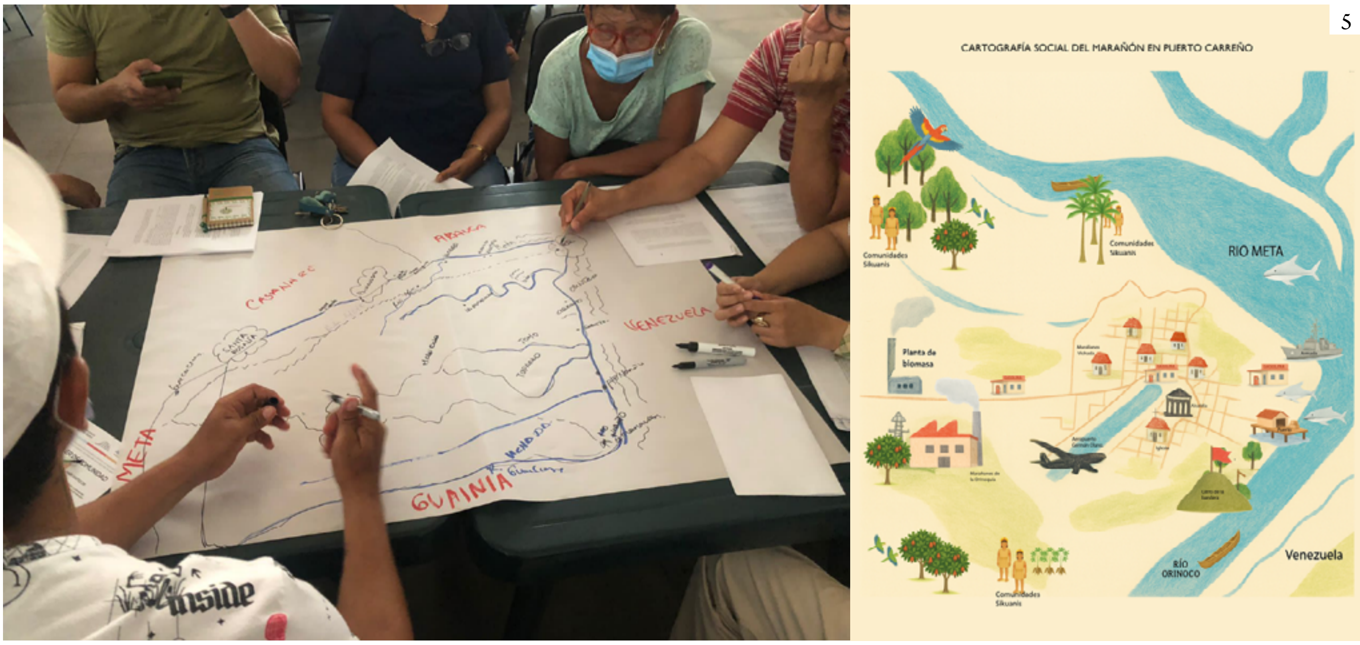

Figure 5 Co-creative workshops of social cartography with the community of Vichada, 2022.

2.2. About the Nut

Taming the Flames, Taking the Shell

As previously mentioned, the cashew fruit consists of a shell approximately two inches in length, which encases the nut and a corrosive, non-edible natural oil (Figure 6). Structurally, the nut is composed of three main components: a tough outer shell (epicarp), a dense inner layer (endocarp) and a valuable edible kernel. While the cashew kernel is a prized nutritional product, it represents only a small fraction of the total fruit weight; the shell accounts for roughly 75% and is often discarded, raising environmental concerns (Prakash *et al.*, 2018).

Botanically, the cashew tree can reach up to 12 meters in height and demonstrates high tolerance to water stress. It begins to bear fruit around its third year of growth and typically reaches peak production by the eighth year. Although it can live for 50 to 60 years, the tree produces much of its fruit during the first two decades of life (de Brito *et al.*, 2018).

Building upon this potential, the Ministry of Agriculture in Colombia implemented a structured land development initiative aimed at fostering cashew cultivation in the department of Vichada. As part of this programme, local residents (particularly smallholder farmers) were granted plots of approximately two hectares where they could establish cashew plantations and gradually integrate into the emerging cashew value chain (CORPOICA, 2015; SADEV, 2020). This effort was intended to promote rural development, diversify local economies, and provide new livelihood opportunities through sustainable cashew cultivation.

However, in regions where cashew processing occurs, the lack of infrastructure and limited technical knowledge among nut processors has made this transformation chain extremely challenging (Figure 7). The shell itself is highly resistant to degradation and provides additional protection against chemical and biological attacks from the environment (Berry & Sargent, 2011). The process of opening the nut is difficult, and within the shell lies a viscous, dark brown oil. This oil constitutes approximate-

Figure 6 Detail of the cashew nut, shell and CNSL within, 2022.

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Figure 7 Manually opening the cashew nutshell, 2022.

ly 30–35% of the total nut weight (Idah *et al.*, 2014), and while it holds significant potential, improper handling can cause severe environmental and health impacts due to its corrosive nature.

Known as cashew nutshell liquid (CNSL), it contains a high concentration of long-chain phenols, such as anacardic acid (70%), cardanol (5%) and cardol (18%; Berry & Sargent, 2011). These compounds make CNSL a promising resource for producing bio-based polymers, synthetic resins and corrosion inhibitors (Patel *et al.*, 2006). However, due to its corrosive properties, CNSL causes a significant number of burns, leading to long-term disabilities and a diminished quality of life for those handling it (Andonaba, 2017). While previous research on CNSL has focused primarily on its chemical composition and potential industrial applications under controlled conditions, this project introduces a novel approach by contextualising CNSL valorisation within a specific socio-territorial and ecological framework. Unlike most existing studies that consider CNSL as an isolated input for bio-based resins or fuels (Padmanabhan & Takalkar 2018; Mazzetto *et al.*, 2009), our research highlights the risks posed by the corrosive oil to the people who cultivate, open and process the cashew. It integrates a co-design methodology rooted in participatory workshops, where local knowledge fosters a broader understanding of outcomes such as safety, human protection and the valorisation of oil in novel applications. Furthermore, by embedding CNSL transformation in a model tied to local livelihoods, this work expands the discourse on circularity to include both material innovation and social justice. Many local residents, some of whom have been granted land for cashew cultivation through government programmes, refuse to engage in the cashew value chain, as the visible risks of handling CNSL often outweigh the perceived economic opportunities.

Our social cartography co-creation workshop (Moore & Garzón, 2010), conducted with the local community, revealed that these risks could be partially mitigated by preventing direct contact with the liquid. These insights will be explained in the following section. Additionally, by integrating local knowledge about traditional uses of CNSL, we identified new opportunities to transform this material into a safer and value-added resource if its corrosive properties could be successfully neutralized.

One traditional use shared by the community involves applying the liquid to immunize wooden structures—such as beams and ranch components—against insects and animals. This local knowledge inspired further scientific exploration. Building on this insight, the chemical engineering team undertook the challenge of transforming CNSL into a non-corrosive substance while exploring a wider range of technical applications. Potential uses identified include CNSL as a natural waterproofing agent for wooden surfaces and construction materials, as well as its potential role in the development of flame-retardant additives for use in wood and composite materials. Furthermore, the team explored its suitability as a base for plasticizers and lubricants, taking advantage of its natural viscosity and rich chemical composition.

Through these combined efforts, CNSL is no longer viewed solely as a hazardous waste product, but as a promising material with the potential to contribute to a circular and community-driven cashew economy.

Parallel to this, the fibrous solid shell left after CNSL extraction offers complementary opportunities for material innovation. Globally, natural fibre-reinforced polymers are increasingly replacing traditional materials due to their sustainability (Corona et al., 2016; Bogoeva-Gaceva et al., 2007; Azwa et al., 2013), offering mechanical properties comparable to conventional alternatives. The cashew shell, rich in lignocellulosic fibres, is a promising local source for such applications.

During the same co-creation sessions, the possibility of replacing common containment items—such as baskets, crates, barrels, and bins—also emerged. These containers, typically made from traditional polymers, often crack, break, or deteriorate rapidly, contributing to local environmental pollution when improperly discarded. Therefore, the opportunity to replace these containers with alternatives made from cashew shell-based materials became both a strong desire of the community and a technical challenge for our research team.

For this branch of the project, the mechanical engineering and design teams committed to developing both the new material and prototype containers. The goal was to fully integrate sustainable cashew shell composites into the production chain, offering environmental and economic benefits to the region.

Our material-centred exploration revealed that what was once seen as waste (the cashew shell) could be transformed into a resource with great potential, aligning with the emerging global trend on materials design for transition (Duarte Poblete et al., 2024) and biomaterials development (Pollini & Rognoli, 2024).

Visits to cultivation farms and processing facilities showed that the shell, rich in oil, is commonly used in cooking processes during nut extraction, a method known as cooked nut opening. In some markets, consumers prefer the flavour of cooked cashew nuts over raw ones. Notably, the ash remaining from this cooking process became an unexpected material input for further development.

Through fire, what once seemed useless revealed its hidden potential. This traditional burning process not only produces ash but also generates knowledge and opportunities. Material design through experimentation became a core methodology (Parisi et al., 2016; Karana et al., 2015). The process began with understanding and exploring the properties and potential of the cashew shell ash. The next phase involved creating, designing and transforming with one's own hands. Finally, the team moved toward replicating and validating and reproducing findings through scientific techniques in the laboratory.

The research focused on developing new sustainable materials derived from cashew shell byproducts. The initial phase involved deep engagement with the territory and the cashew production chain. Rather than approaching the process purely from a technical perspective, the team adopted a recognition-based approach identifying material sources, understanding production processes, and mapping how environmental conditions influence material behaviour.

Situated knowledge from the region was key. Conducting actor-mapping workshops with the community (Gopal & Clarke, 2015) allowed the community to express needs and expectations while enabling design and engineering teams to value local insights alongside physio-chemical knowledge of materials.

Once this qualitative information was compiled and analysed, the second phase of experimentation began. Using DIY-Materials development approaches (Rognoli et al., 2015; Rognoli & Ayala-Garcia, 2021) and free experimentation through tinkering (Parisi et al., 2017), the team produced a broad range of material samples. These rapid, creative iterations leveraged diverse production techniques and combined raw materials to explore innovative possibilities (Figure 8).

The resulting material samples were evaluated and parameterized with the goal of identifying those with the highest potential. Selected samples were then replicated under controlled laboratory conditions with engineering teams. Through this process, the properties and qualities of the materials were established, laying the foundation for determining their application opportunities, production requirements, and potential for scaled development within the cashew value chain.

Laboratory-produced material samples supported a comparative, materials-driven exploration developed collaboratively by the design and engineering teams. This experimental phase employed biodegradable thermoplastic polymers—specifically polylactic acid (PLA) and thermoplastic starch (TPS)—alongside a conventional thermoset epoxy resin. The primary goal was to examine the plasticizing potential of cashew nut shell liquid (CNSL) and to evaluate the technical feasibility of incorporating cashew nutshells (CNS) and CNS-derived ash as fillers in composite formulations.

CNS was ground using a blade mill to obtain particles

Figure 8 Material experimentation with cashew nutshell and ash, 2023.

smaller than 1000 µm and subsequently dried in a convection oven at 60 °C for 24 h. PLA-based composites were compounded using an internal mixer (Brabender Plasticorder 331) at 180 °C and 60 rpm for 7 min to achieve uniform dispersion of CNS particles. The resulting material was pelletized and compression moulded into 100 mm × 100 mm films at 180 °C and 110 bar using a LabTech press. TPS-based formulations were prepared with cassava starch, employing a 30:100 starch-to-water ratio, processed at 75 °C for 1 h, cast into rectangular moulds (100 mm × 100 mm), and dried at 20 °C for 48 h. Thermoplastic composites containing 10–40 wt.% CNS byproducts were obtained.

Epoxy-based materials were produced through a casting process in which CNS particulates were dispersed into the resin and hand-mixed until homogeneous. Formulations containing 50 wt.% CNS were cast and cured at 20 ± 2 °C for 24 h. This series of formulations enabled the team to assess the influence of CNS-derived materials on composite behaviour and to establish the foundations for further material experimentation within the Jurui framework.

Once these initial "potential materials" were obtained and characterized, they were presented to the Vichada community in an accessible material sample format. Dedicated workshops used expressive-sensory evaluation (Rognoli & Levi, 2005; Parisi et al., 2016), enabling community members to assess the materials based on their tactile, visual, and functional qualities. These workshops amplified local knowledge, validated the research findings, and informed the ongoing material and product design process (Figure 9). Additionally, the sessions helped

Figure 9 Material co-creation workshops with the community, 2023.

dissolve initial biases around the materials and opened new pathways for community-driven co-creation of future applications. The most promising materials selected by the Vichada community were evaluated to determine their mechanical performance. Tensile and hardness properties were assessed in accordance with ASTM D3039 and ASTM D2240 standards, respectively (ASTM International, 2017; ASTM International, 2016).

For tensile testing, rectangular specimens (80 mm × 10 mm) of Epoxy/50 wt.% CNS and TPS/40 wt.% CNS ash composites were prepared and tested using an Instron 3367 universal testing machine equipped with a 30 kN load cell. Tests were performed at a crosshead speed of 5 mm/min with a gauge length of 30 mm. Four replicates were tested per material.

Shore D hardness was determined using a Shore 313x digital durometer (ZwickRoell) with a type D indenter and a 50 N load. Ten measurements were taken at different positions on each specimen. The tested materials included Epoxy/50 wt.% CNS, PLA/10 wt.% CNS, PLA/40 wt.% CNS, and TPS/40 wt.% CNS ash.

Representative stress–strain curves obtained from the tensile tests for thermoset and thermoplastic-based composites are presented in Figure 10, and Table 1 summarizing the main mechanical properties. The epoxy composite exhibited a tensile strength 11.6 times higher than that of the TPS-based material (0.35 MPa vs. 4.06 MPa) and an elastic modulus approximately 20 times greater (14 MPa vs. 280 MPa). Both materials demonstrated a strain at break exceeding 20%.

In the epoxy system containing 50 wt.% CNS, the observed ductility and relatively low stiffness may be attributed to the presence of residual cashew nutshell liquid (CNSL) within the shells (approximately 50 wt.% of the nutshell), which acts as a plasticizer for the resin. Conversely, the TPS-based composite exhibited the characteristic ductile behaviour of thermoplastic materials, consistent with their lower stiffness (Zhang et al., 2014). The overall reduction in tensile properties observed in both systems can be associated with the large and non-uniform particle size distribution of the CNS and CNS ash fillers (Fu et al., 2008).

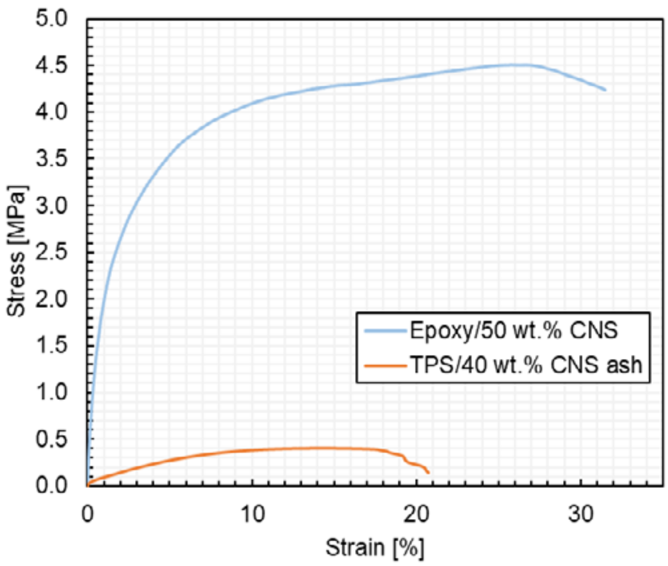

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Figure 10 Tensile stress-strain curves of CNS-based materials.

Material	Tensile strength [MPa]	Elastic modulus [MPa]	Strain at maximum load [%]
Epoxy/50 wt.% CNS	4.06 (0.46)	280.13 (35.24)	23.11 (7.08)
TPS/40 wt.% CNS ash	0.35 (0.10)	14.15 (1.04)	12.80 (4.12)

Table 01 Tensile properties of CNS-based materials.

Fractured tensile specimens are presented in Figure 11. Non-uniform CNS particles with limited interfacial adhesion, attributed to the superficial presence of CNSL, act as stress concentrators within the composite. In the epoxy matrix, the residual CNSL and the relatively coarse particle size and irregular distribution of CNS may deflect the crack front, induce crack bridging and particle pull-out, enhance fracture energy, and promote incomplete crack propagation with distributed damage, thereby preventing total specimen separation.

Conversely, the TPS-based composite displays a ductile fracture behaviour characterized by localized tearing prior to failure. This response is attributed to the low stiffness of the TPS matrix and its water-induced plasticization, both of which enhance matrix deformability and energy absorption during loading.

The Shore D hardness values for the thermoset- and thermoplastic-based composites are shown in Figure 12. The measured Shore D hardness for Epoxy/50 wt.% CNS, PLA/10 wt.% CNS, PLA/40 wt.% CNS, and TPS/40 wt.% CNS ash were 68.9, 35.9, 48.7, and 39.8, respectively. In PLA-based composites, higher CNS content (40 wt.%) resulted in increased hardness, suggesting effective filler–matrix interaction and reinforcement. Comparable trends have been reported in previous studies; for example, the Shore D hardness of neat PLA increased from 78.65 to 85.05 upon incorporation of 50 wt.% torrefied coffee husk (Ortiz-Barajas et al., 2020).

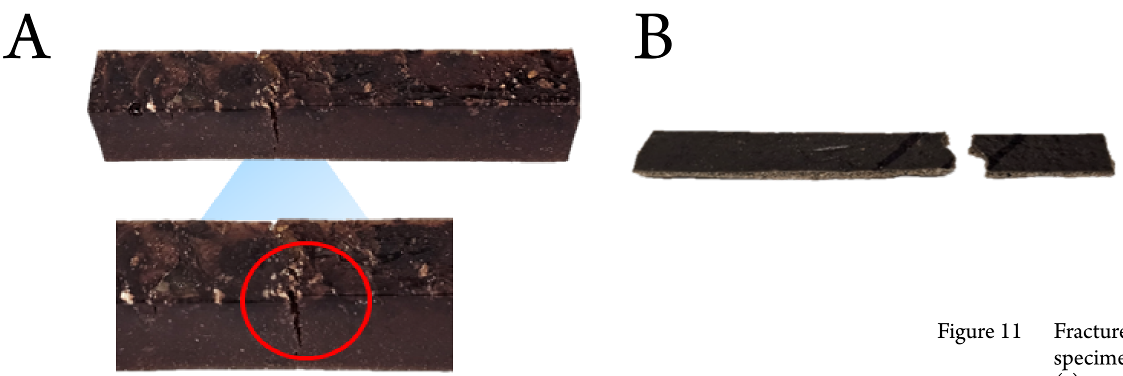

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Figure 11 Fractured CNS-based tensile specimens.
(a): Epoxy/50 wt.% CNS, and
(b): TPS/40 wt.% CNS ash.

12

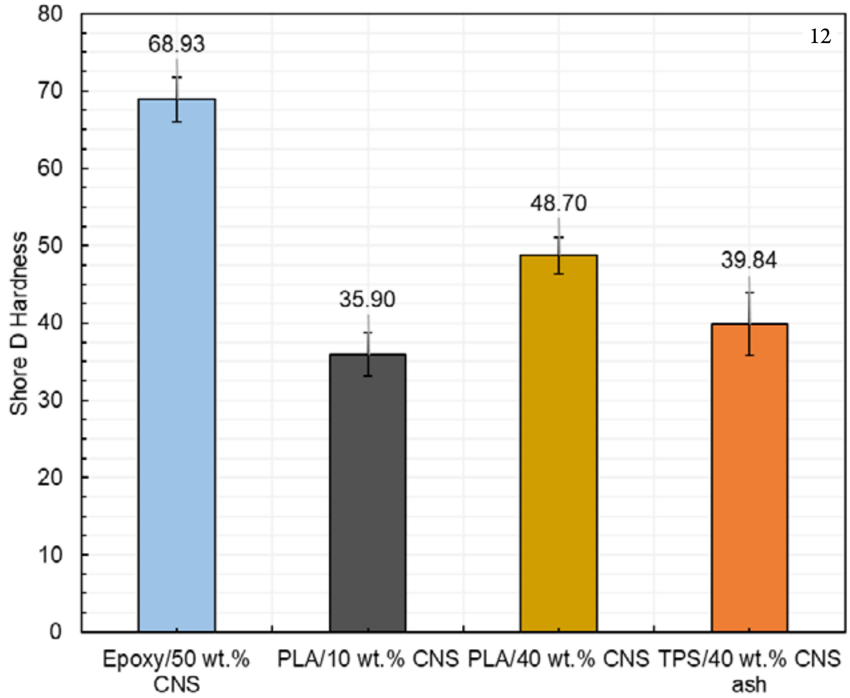

Figure 12 Shore D hardness of CNS-based samples.

Parallel to laboratory formulation, our design team worked to understand how packaging is used across the cashew value chain. We observed how bags, baskets, and pallets are employed in everyday practices, identified where new packaging was needed, and explored how existing solutions could be improved (Figure 13). Significant opportunities were found to replace conventional plastics with more sustainable cashew shell-derived materials.

In a dedicated ideation phase, packaging design concepts were developed—drawing inspiration from natural forms and specific use cases. Rapid, functional sketches explored modular, ergonomic, and sustainable solutions that addressed everything from grip and handling to storage and transport. Low-resolution prototypes were then constructed to validate form, scale, and assembly.

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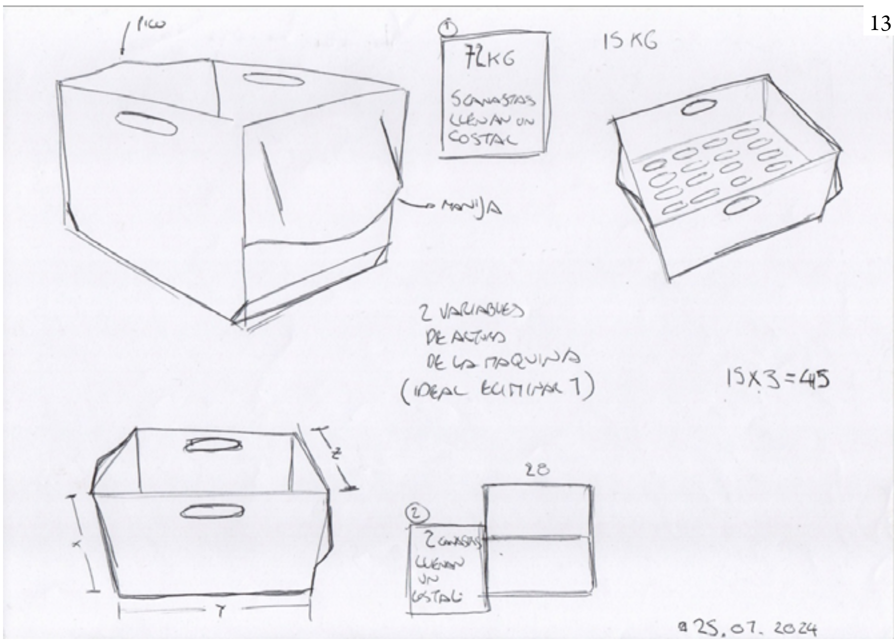

Figure 13 Some sketches of the packaging ideation phase.

2.3. About the People (Results)

Well-being as a Driver of Growth

People are one of the key elements of sustainable development. As we confront the impact of human activity on the planet, it becomes evident that fostering harmony with our environment must go hand in hand with enabling people to thrive. Addressing wicked problems such as poverty and low quality of life is essential. In our project, it became clear that any development using materials derived from cashew must also contribute directly to improving the well-being and dignity of the people in the region.

One of the key findings from the co-creation process was the need to fully isolate human contact from the nut-opening process, in order to minimize exposure to raw cashew nutshell liquid (CNSL) and prevent further injuries. In response, the mechanical engineering team, in collaboration with the design team, committed to developing a low-cost nut-opening machine. Crucially, this equipment was conceived to be built locally and maintained by regional mechanical experts—such as motorcycle repair workshops—thereby reducing dependence on external technical support.

Cashew nuts are a globally significant product, driving the development of many agribusinesses. In 2018, Vietnam led global production, followed by India, with Brazil ranking ninth in South America. However, despite impressive in-shell cashew production volumes, the process of shell removal and nut recovery remains labour-intensive, involving multiple manual stages. This not only limits overall process efficiency but also creates significant occupational hazards, particularly in regions where traditional processing methods dominate.

In regions such as Vichada, where cashew processing occurs, the lack of infrastructure and limited technical knowledge make CNSL a serious hazard. Due to its corrosive properties, the oil causes numerous burns, leading to long-term disabilities and a diminished quality of life for those who handle it. Alarmingly, many local residents—some of whom have been granted land for cashew cultivation through government programmes—refuse to enter the cashew value chain because the visible risks of handling CNSL outweigh the perceived opportunities.

In pursuing a sustainable economic model for cashew production in the Vichada region, it is essential to recognise that progress cannot rely on replicating highly automated, capital-intensive technologies used in other agro-industrial contexts. Vichada faces infrastructural limitations—such as unreliable road networks and unstable electricity supplies—that make high-tech solutions impractical. More importantly, any innovation must respect local realities, skills and knowledge systems.

Through close engagement with local communities, our team learned that many technological challenges in Vichada are addressed through ingenuity and traditional wisdom. This insight led us to prioritise the development of appropriate technologies—solutions designed to

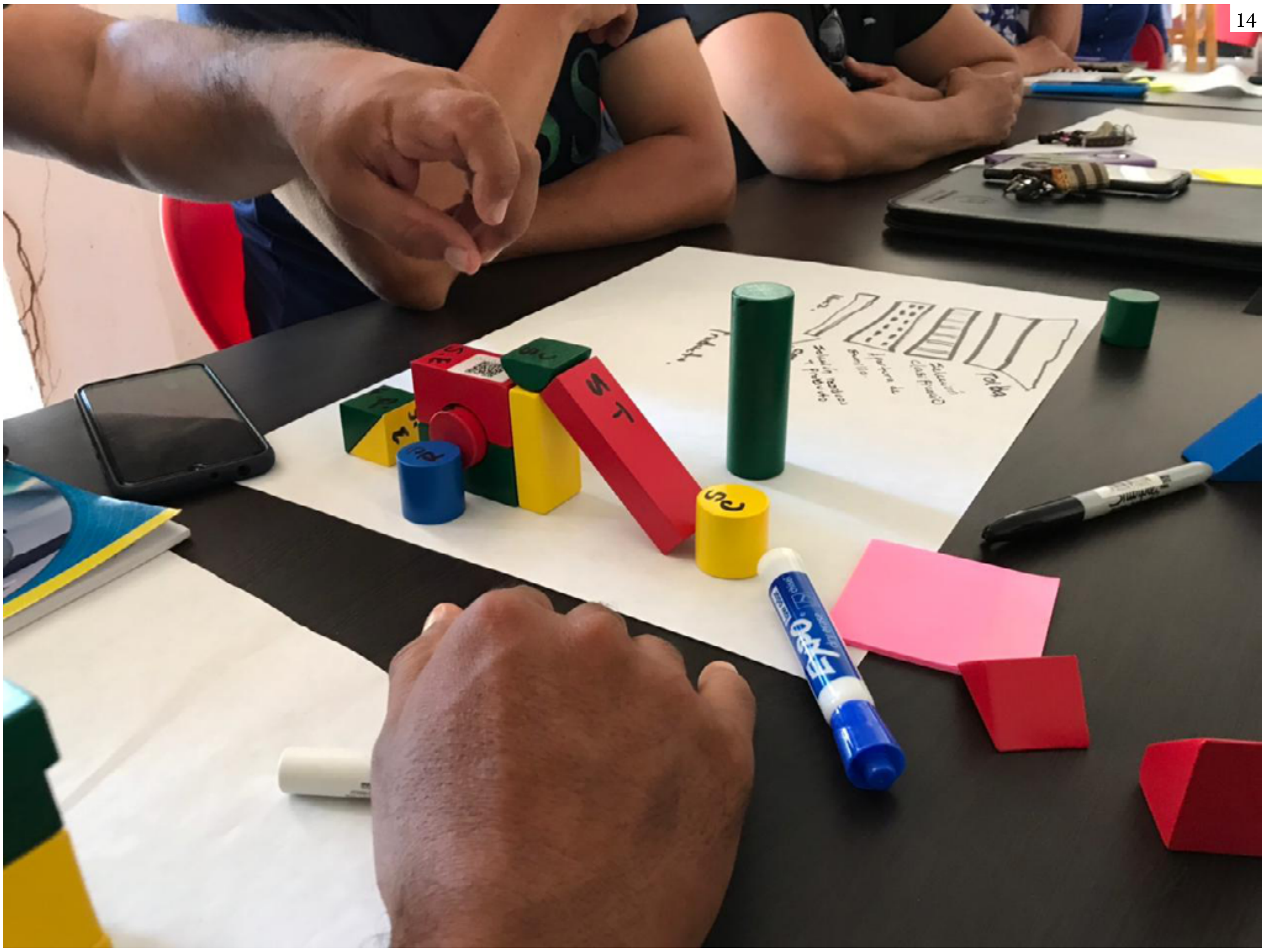

Figure 14 SCAMPER workshop with the community, 2023.

match the region's technical, social and economic fabric.

A central innovation emerging from this approach is the development of a mechanical nut-opening machine that minimises direct human contact with corrosive CNSL. In designing this machine, ergonomic considerations were essential. Understanding how local people interact with the cashew transformation process—how they move, position themselves and manage various stages of processing—was key to designing equipment that would offer not only technical efficiency but also safety and usability.

To ensure the machine would truly meet local needs, we conducted a participatory workshop where local processors were invited to contribute their ideas and preferences. Using the SCAMPER technique (Eberle, 1996), we systematically explored and integrated community knowledge with technological requirements (Figure 14). This process generated multiple promising configurations, which were carefully evaluated by the engineering team to identify the most feasible design for development.

For the machinery development, we followed a methodology of *common principles prototyping* (Camburn, *et al.*, 2017). The engineering team first defined optimal performance requirements, while the design team explored these through low-resolution prototypes (Figure 15). Each prototype tested real nut sizes, positioning methods for opening without damaging the nut and configurations to achieve minimum or no contact between the liquid and the user's hands or body. Ergonomic considerations were also central, particularly in relation to the integration of the crates, and to ensure that the machinery supported efficient manual separation of nut and shell.

Once core technological principles were validated, a parallel human-centred design process was launched to ensure that the equipment could be used in ways aligned with ergonomic standards and local traditions. Many experienced cashew processors possess deep expertise in selecting and grading nuts to meet specific market demands, a process still performed by hand. This valuable skill should not be replaced by automation; rather, the goal was to enhance these traditional practices through improved work environments (Figure 16).

An important feature of the new machinery is its ability to facilitate the collection of opened shells for reuse in oil extraction and material development. Once the machine's design aligned with both community expectations and the technical parameters defined by the team, the engineering team built a high-resolution prototype capable of cutting nuts and sustaining weekly production tests. After refining and optimising this prototype, it was transported to the region for user testing, where its production performance and adaptability to local working conditions were evaluated in real settings.

Ultimately, the project successfully transformed cashew residues into a new material, merging scientific rigour with creative design. Sustainable packaging prototypes were validated with real users from the Vichada community (Figure 17). Engineering challenges such as ensuring material resistance, managing colour changes, and mitigating ageing were addressed through collaborative development.


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Figure 15 Low resolution prototypes for cashew nutshell opening, 2023.


16

Figure 16 Low resolution prototypes and final machinery development for cashew nutshell opening and separation, 2025.

17

Figure 17 Packaging solution prototypes for cashew production tested on-site with local producers, 2025.

Real prototypes were produced via 3D printing and injection moulding in partnership with industrial collaborators, marking a critical step towards scaling cashew shell-based packaging for commercial use (Figure 18).

A sustainable cashew transformation chain in Vichada must remain centred on people. If local farmers, processors and landowners can see that participating in the cashew value chain no longer comes at the expense of their health and well-being, they will be far more likely to engage and invest in this economic opportunity. By placing well-being at the heart of growth, our project seeks to foster not only a more productive cashew sector but also a more inclusive, dignified and resilient rural economy.

Figure 18 Final packaging prototype for cashew production chain, 2025.

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To facilitate this goal, we placed the prototypes in the region's national centre for training and education, Servicio Nacional de Aprendizaje (SENA). There, specific training courses will be provided to community members to support the integration of this technology into the actual production chain. The courses will teach participants how to operate the machine safely, highlighting how such equipment protects them from injuries while also modestly improving production speed.

One of the key principles in the machinery's design is that its blueprints are open-source and made freely available to the community through the local government. This approach enables additional segments of society, such as local workshops or entrepreneurs to participate in the production chain by manufacturing the machinery according to the established standards. To ensure safe and consistent use, SENA will also oversee a basic quality control process, helping to prevent misuse or manufacturing failures that could compromise performance or user safety.

2.4. About the Place (Discussion)

Vichada, like many regions around the world where nutritious, valuable agricultural products are cultivated for global markets (Figure 19), faces deep multidimensional marginalisation. Access to critical infrastructure such as transportation networks, water and waste management systems, and investment capital remains limited. Too often, regional development efforts prioritise the transformation of the food source itself (which holds economic value), without ensuring that this value returns to local communities or contributes to sustainable territorial development.

In designing this project, we explicitly chose to link development of the land, its ecosystems and communities, with the transformation of the cashew nut and its by-products. This priority was driven not only by the project's original goals but also by the many insights gained through extended engagement in the region. The more we immersed ourselves in Vichada, the clearer it became that we must resist repeating patterns seen elsewhere, where technological agro-industrial development leads to water pollution, environmental degradation and the loss of fragile ecosystems (Food and Agriculture Organization, 2021b).

Vichada is home to some of the most extraordinary biodiversity in the Orinoco basin. It is a habitat for endangered species such as the pink river dolphin (*Inia geoffrensis*; da Silva, 2023), locally known as *toninas*. The region also contains unique geological formations, including ancient rock outcrops such as the

Figure 19 Vichada cashew nuts after opening and extraction, 2025.

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Cerros de Mavecure, and is part of one of South America's most important and sensitive freshwater ecosystems (Castello *et al.*, 2013).

If we are to foster technological innovation to improve cashew production and enhance local livelihoods, we must do so without compromising this rich natural heritage. In this spirit, we proposed a technological development model that deliberately avoids driving unsustainable infrastructure expansion. Instead, it leverages existing infrastructures and ecological dynamics.

One concrete example is transportation. The region's lack of paved roads, combined with vast distances and challenging terrain, makes land-based logistics costly and unsustainable. However, rivers remain a traditional and ecologically sound means of transportation and have a huge potential for sustainable development in the near future (Hunt *et al.*, 2022). The Orinoco and its tributaries have long served as vital arteries connecting communities and facilitating commerce across Colombia, Venezuela and the Guianas.

Another key strategy is the localisation of production in rural areas (Woods, M. 2005), based on the use of by-products developed during the project. The goal is for all machinery, moulds for the containers and manufacturing processes to be implemented *in situ*. This approach ensures that the region is not forced to rely on the infrastructure of major cities (which are distant and reachable only by air). Instead, all resources can be collected and processed within the cashew production chain itself. The various products, prototypes and artifacts developed during this project demonstrate this potential to establish a circular system that the region can leverage, while efficiently exporting the cashew nut to both local and international markets.

Rather than promoting models that rely on exporting raw cashew products through centralised hubs in the country's interior, our project began exploring decentralised value chains that could integrate with the existing fluvial transport system. This approach would enable local processing and value addition, reducing the need for long-distance overland transport and allowing cashew-based products to reach both domestic and international markets via river routes while preserving the region's ecological balance.

This research also contributes to emerging global trends in sustainable materials and design by reframing agricultural by-products as active agents in a bio-based circular economy. While much of the global discourse around biomaterials emphasises industrial scaling and technological efficiency, our work demonstrates an alternative model rooted in materials design (Duarte Poblete *et al.*, 2024; Pollini & Rognoli, 2024), territorial integration, and participatory innovation. By merging cashew shell fibres and CNSL into new composite materials, coatings and additives co-developed with local communities, the project aligns with international efforts to advance regenerative bioeconomies and sustainable supply chains (Ellen MacArthur Foundation, 2013; Mesa, 2024). It further extends the scope of biomaterial research by embedding social and cultural dimensions into material development, demonstrating that material innovation can simultaneously support environmental stewardship, local economies, and cultural resilience.

To support this vision, we are also examining alternative economic models that encourage territorial integration and cross-border collaboration. By aligning technological, ecological and social considerations, we aim to foster a cashew value chain that enhances both the prosperity of local communities and the resilience of Vichada's natural environment.

Vichada should not be forced into replicating agro-industrial models that have degraded so many other tropical landscapes. Instead, it offers an opportunity to pioneer a new model of place-based innovation, where economic growth is intimately linked to the health of local ecosystems and the cultural vitality of its people, thanks to the holistic integration of an edible material and its derivations.

6. Conclusions

Exploration of the cashew nut, its people and its place in Vichada has revealed how deeply interconnected material, social and territorial dimensions truly are. We began a project focused on valorising cashew by-products but evolved into a broader reflection on how design, engineering and community participation can foster new forms of sustainable innovation.

From a material perspective, the cashew shell and its by-products, which were once viewed largely as waste, become valuable resources with potential applications in packaging, composite materials, surface treatments and industrial processes. The transformation of cashew nutshell liquid (CNSL) into safer, value-added materials and the development of bio-based materials from cashew shell residues show how a material-centred approach can open new circular opportunities within local economies. Moreover, the creation of tools and machines adapted to local capacities has helped to build a foundation for Vichada local residents to participate in the cashew value chain in a safer, more dignified way.

The co-creation processes with local communities ensured that technologies were not imposed from outside, but instead emerged from dialogue and mutual learning. The nut-opening machine development, ergonomic improvements to workspaces, and participatory workshops all sought to empower local processors and reduce health risks, making well-being a central driver of innovation. Ultimately, these efforts aim to foster a more inclusive, resilient and people-centred cashew sector in the region.

Finally, the project's territorial dimension highlighted that innovation cannot be separated from place. Vichada is a living territory, rich in biodiversity, culture and local wisdom. The project consciously avoided adopting industrial models unsuited to its fragile ecosystems and infrastructure. Instead, it proposed strategies of localisation, circularity and ecological sensitivity. Decentralised production models and locally sourced manufacturing pathways offer a vision for a cashew economy that supports both local livelihoods and environmental stewardship.

In sum, in this article, we want to present how this interdisciplinary project, one that is deeply connected with the community, opens real possibilities to reimagining matter, whether a nut, a shell, an oil, or a material. It also explains how such approach can also transform relationships: between people and their land; between design and tradition; and between economy and ecology. The Jurui project points towards new ways of honouring the relational nature of materials, technologies and territories, offering a blueprint for future efforts in sustainable and community-driven innovation.

Acknowledgment of Author Roles

Camilo Ayala-Garcia: writing – original draft preparation, methodology development and design lead for materials, packaging development and machinery; analysis and interpretation of results; writing – review and editing.

Clara Ligia Forero: field research; integration of qualitative data and visual documentation; Jurui brand development.

Santiago De Francisco Vela: co-creation workshops lead; data collection; writing, review and editing.

Alejandro Marañón León: material characterisation lead; packaging development and viability data collection; writing, review and editing.

Camilo Hernández Acevedo: machine development and construction lead.

Oscar Álvarez Solano: CNSL transformation lead.

Alicia Porras Holguín: study conception and project lead; writing, review and editing.

All authors have read and approved the published version of this manuscript.

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Additional Data Availability
https://proyectojurui.uniandes.edu.co/productos-de-investigacion/

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