Biodegradable Ecological Roof Tile for Andean Rural Architecture: Circular Design Using Low-Impact Organic Materials

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***Abstract*– This study presents the development and validation of an ecological roof tile made from organic compounds, conceived as a technical-environmental solution to construction and demolition waste (CDW) in highly vulnerable rural areas. Through an experimental approach, mixtures composed of sieved soil, horse manure, potato starch, vegetable shortening, and water were designed and evaluated across 15 successive trials using standardized molds. The final mixture demonstrated optimal conformability, morphological stability, structural cohesion, and preliminary mechanical resistance after natural drying. During its service phase, the inclusion of vegetable shortening creates a hydrophobic layer that limits moisture absorption, thus extending its functionality as a roofing component. In the event of structural fracture, this film disintegrates, allowing gradual water ingress and activating the material's compostability as an organic soil conditioner. This dual functionality aligns with principles of circular design, enabling the material to transition from a constructive system to an agroecological input without requiring industrial recycling. The proposal was qualitatively validated through expert judgment and received international recognition in invention competitions, reinforcing its technical feasibility and replicability potential. Overall, the findings establish the ecological tile as a sustainable alternative for rural architecture, with a positive impact on both habitability and the circular management of materials in resource-limited settings.**

***Keywords*-- Bioconstruction, compostable materials, rural architecture, circular design, organic waste.**

I. Introduction

Environmental sustainability has become a critical global priority across all disciplines, underscoring the urgency of reusing waste materials while reducing the extraction and use of non-renewable resources. This valorization of resources is particularly relevant in contemporary architecture, where sustainability is a pressing necessity [1]. According to the Global Waste Management Outlook from the United Nations Environment Programme, global solid waste generation is expected to reach 3.8 billion tons, with construction and demolition waste (CDW) [2][3] constituting one of the most significant waste streams surpassing 10 billion tons. Industrialized nations contribute substantially: the United States generates approximately 700 million tons, the European Union over 800 million tons, and China produces 2.3 billion tons of CDW annually [4][5].

In Peru, the CDW situation is particularly concerning due to a lack of official research or quantification, despite visible street-level accumulation and the need for cleanup operations [6][7]. Reports indicate a 7% increase in CDW between 2023 and 2024 [8], highlighting a growing problem. According to the Peruvian General Law on Solid Waste (Law No. 27314), CDW is defined as waste generated during the construction, expansion, remodeling, demolition, or rehabilitation of buildings and infrastructure [9]. Legislative Decree No. 1278 classifies CDW as non-municipal waste, although district municipalities are responsible for its supervision and regulation [10]. Among the components of CDW, ceramic roof tiles present a particular challenge due to their fragility, limited recyclability, and persistence as inert non-biodegradable materials.

In the rural architectural context, this issue takes on a distinct dimension, especially across Peru's three natural regions (coast, highlands, and jungle) with a concentration in the Andean region. Here, towns and villages are characterized by rugged terrain, logistical constraints, and limited access to transportation infrastructure. Self-built housing often relies on local materials such as stone, adobe, and wood [11]. As depicted in Fig. 1, which shows a dwelling on the outskirts of Cusco, the structure is composed of adobe and wood, while the roof uses ceramic tiles.

Compared to urban housing, which predominantly uses reinforced concrete (52.5%) and corrugated metal sheets (38.9%) for roofing, rural dwellings report 18.1% usage of ceramic tiles the second most utilized material since 2013 [12]. Fig. 2 illustrates urban rooftops in Cusco, clearly showing the widespread use of ceramic tiles.

However, these ceramic tiles are typically manufactured in distant urban centers, increasing both the economic and environmental costs of construction due to their heavy weight, fragility, and high energy footprint associated with high-temperature kiln firing [13]. Moreover, transportation and installation of ceramic tiles involve a high breakage rate, generating unrecyclable waste that accumulates in natural or agricultural settings.

In Peru, no specific national technical standard (Norma Técnica Peruana - NTP) or construction regulation under the National Building Code (Reglamento Nacional de

Edificaciones - RNE) directly governs the use of ceramic tiles, except for general references to load standards (NTP E.020) [14] and seismic-resistant design (NTP E.030) [15].

Fig. 1: Photograph of a house on the outskirts of the city of Cusco – Peru

Fig. 2: Photograph of houses along a street in the city of Cusco – Peru

Within the broader framework of sustainable architecture, the use of low-impact materials that integrate easily into natural cycles is essential [16]. Current research increasingly emphasizes solutions that are both functional and regenerative, focusing on construction elements derived from agricultural by-products and organic waste [17].

The need to rethink roofing materials from architectural, territorial, and ecological perspectives has led to the development of alternatives based on the efficient use of agro-industrial waste. This article presents an ecological roof tile composed of biodegradable residues such as potato peel, starch, horse manure, and sieved soil. Individually, these elements have limited utility, but when combined, they yield a biodegradable material capable of replacing traditional ceramic tiles. Notably, this mixture requires no high-temperature processing, significantly reducing its energy footprint and allowing for small-scale local production.

The ecological tile is positioned as a viable response to architectural challenges in remote and difficult-to-access regions, where the cost of conventional materials is inflated by transportation, and where traditional construction strategies must be reinforced without compromising cultural identity or ecological balance. Composed of readily available materials in Andean rural settings, the tile supports local manufacturing, community training, and sustainable value chains at the microterritorial level.

From an architectural standpoint, the innovation of this tile lies not only in its physical and mechanical properties but also in its socio-territorial relevance. It adapts well to self-construction practices, integrates with local knowledge, and offers a context-appropriate solution for many rural communities in Latin America. Ultimately, this proposal reimagines rural roof design by considering resource availability and waste minimization through an environmentally conscious and socially inclusive lens.

II. Methodology

This research was structured into three successive phases, designed to develop a multidisciplinary approach that integrates the diagnosis of the Andean rural context, sustainability criteria in the experimental design of constructive compounds, and their qualitative evaluation under real application conditions. Throughout these stages, local knowledge, sustainability principles, and technical criteria were combined for the development of alternative building materials.

A. Phase I: Context diagnosis and material selection

In this phase, organic materials available in rural Andean communities that could be valorized for manufacturing construction components were identified. Through direct observation in central highland areas of Peru, local practices related to organic waste management and vernacular construction techniques were documented. This fieldwork was complemented by a literature review focused on bioconstruction, circular economy applied to architecture, and the use of organic materials in sustainable architecture. Methodological tools included characterization sheets for waste types (animal manure, tuber peels, sieved earth) and systematized photographic records of observed field practices.

B. Experimental design of constructive compounds and preliminary characterization

During this phase, experimental mixture combinations were developed through an iterative empirical approach. Varying proportions of sieved soil, horse manure, boiled potato starch, and potato peel were used. The mixture was molded using artisanal tools with a uniform kneading time per unit. Physical characterization was performed using technical datasheets that recorded variables such as consistency, plasticity, surface texture, odor, and conformability in both fresh and dried states. This process enabled the selection of the mixture with the best physical-constructive performance.

C. Phase III: Qualitative evaluation in a constructive context

Finally, an integral evaluation process of the ecological tile prototype was implemented in a simulated rural structure. This phase included the installation of an experimental roof and the creation of a digital model of the roofing system. For analysis, a qualitative evaluation matrix was designed with criteria including biodegradability, weight, estimated environmental impact, manufacturing cost (materials and labor), type of labor used in installation, compatibility with traditional construction techniques, and aesthetic perception. Each criterion was assessed on a five-level Likert-type qualitative scale (1 = very poor, 5 = excellent), allowing for a contextualized and replicable understanding of the material's performance in its architectural application. Additionally, a comparative evaluation with conventional roofing materials was conducted.

III. Results

A. Physical-constructive characterization of the mixture

During the elaboration and processing phase of the compound material for the ecological tile, key physical-constructive properties were identified, supporting its applicability in low-tech sustainable architecture. The mixture exhibited a semi-plastic, highly moldable consistency, suitable for manual shaping without synthetic additives. Kneading time, approximately 10 to 15 minutes per unit, enabled effective adaptation to a concave rectangular mold without collapse or deformation, evidencing morphological stability in the plastic state. This condition renders it a viable solution for rural contexts with limited technological resources, aligning with appropriate architecture approaches [18].

In its fresh state, the material presented a uniform brown coloration without spots or visible heterogeneities, which remained stable after natural drying, without signs of surface oxidation. The odor was neutral with mild organic notes, and the texture was slightly coarse with visible fibers, lending the material an artisanal identity consistent with bio architecture practices (Fig. 3).

In terms of cohesion and adherence, the mixture demonstrated high internal structural integrity, with no shrinkage cracks or detachments during natural curing. This behavior is attributed to the incorporation of potato starch, derived from organic waste, which acted as a natural binder enhancing component integration (Fig. 4). This finding aligns with studies on bio-based binders in environmentally low-impact construction materials [19].

Fig. 3: Appearance of the mixture in fresh state (left) and after drying (right).

Fig. 4: Potato peel waste from a local restaurant

B. Constructive Performance and Experimental Evaluation

The constructive performance was assessed based on parameters related to dimensional stability, drying time, morphological conformity to the mold, and the behavior of experimental compound designs. During the molding phase, 15 independent experimental trials were conducted. In all cases, the mixture retained its shape in standardized molds without collapses or deformations due to excess moisture or lack of cohesion, demonstrating an adequate balance between plasticity and rigidity (Fig. 5). Likewise, no volumetric losses were recorded during demolding, indicating its suitability for manual production processes without the need for specialized mechanical compaction equipment, a key condition for implementation in rural settings with technological constraints.

Natural drying was completed within 72 hours at ambient temperatures (18 to 24 °C), without the use of assisted drying processes involving induced heat. The pieces maintained structural integrity with no cracking or delamination. Once drying was completed, the tiles achieved preliminary mechanical strength suitable for handling and installation, validating their stability against mild mechanical stresses, particularly those associated with manual assembly and transportation in rural construction systems. However, under adverse environmental conditions (temperatures <15 °C or high relative humidity), the drying process may double or triple, thus optimization under controlled climate conditions is recommended.

Fig. 5: Mold (right) and shape retention of the tile during the post-molding stage (left)

To assess different mixtures, an experimental matrix was designed using qualitative criteria (Likert scale from 1 to 5) including consistency, workability, color, and odor. Table I summarizes the technical analysis of three experimental variants resulting from different combinations of organic compounds in variable proportions. The mixture composed of sieved soil, horse manure, potato starch, vegetable shortening, and water yielded the most favorable performance. This experimental design optimized texture, cohesion, relative impermeability, and structural behavior of the compound without the use of synthetic additives (Fig. 6).

TABLE I
TECHNICAL DATASHEET

Criteria	Description	P1: < soil	P2: < manure	P3: < shortening
Consistency	Determines physical stability during handling, cohesion, and firmness	5	3	2
Workability	Ease of working the mixture during pouring and/or molding	5	4	3
Color	Visual appearance considering texture and aesthetics	5	4	3
Odor	Olfactory perception of the mixture	5	2	2
Total		20	13	10

Note Evaluation conducted during the mixing and drying phases for each proportion

The sieved soil provided initial mechanical rigidity, acting as granular support within the composite system; the manure contributed vegetal fibers (secondary structural component) and macronutrients; the starch integrated the components as a natural polymer; the shortening created a hydrophobic film that enhanced moisture resistance; and the water activated the necessary physicochemical reactions. This formulation exhibited a continuous fissure-free surface, strong mold adherence, ease of handling, and adaptability to artisanal processing fundamental conditions for its replicability in rural communities. The figure presents the relative percentages of the components used in the experimental design of construction compounds for the ecological tile. The radar chart illustrates the evaluated minimum and maximum ranges for each component (sieved soil, horse manure, potato starch, and shortening), reflecting the technical control applied throughout the design iteration process.

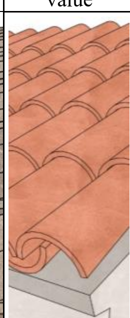
Fig. 6: Percentages of optimal ingredients for the ecological tile material

C. Qualitative Evaluation: Comparison with Commercial Tiles Available in the Peruvian Market

A comparison matrix was developed involving conventional roofing tiles commonly used in rural areas of Peru: clay tiles, Andean fiber cement tiles, and polypropylene tiles. The ecological tile outperformed in indicators such as biodegradability, environmental impact, and compatibility with vernacular construction systems, although it still requires further technical validation regarding long-term durability (Table II).

During compostability evaluation, the material was exposed to both humid environmental conditions (with relative humidity exceeding 90% and contact with moist soil) and dry conditions. In humid environments, signs of biodegradation such as microbial growth and mass loss were observed, confirming its potential as an organic fertilizer.

TABLE II
COMPARATIVE ANALYSIS OF ROOFING TILES MADE FROM DIFFERENT MATERIALS TYPE

Characteristics	Ecological Tile	Clay Tile	Andean Fiber Cement Tile	Polypropylene Tile
Material	Organic	Non-renewable (clay)	Cement + synthetic fibers	Petroleum-derived polymer
Biodegradability	5 100% organic	3 natural but not compostable	1 non-biodegradable, contains cement	2 recyclable plastic, not compostable
Average Weight	4 approx. 1.5 kg	2 2.5–3.5 kg	3 approx. 8.4 kg	5 < 2.4 kg
Environmental Impact	5 reused waste, no kiln needed	2 high-energy kiln process	2 cement + artificial fibers	3 plastic, but recyclable
Manufacturing Cost	5 local, low-cost materials	3 requires kiln, specialized process	4 Industrial, accessible in cities	4 medium cost
Installation	4 manual, simple	3 requires placement skill	4 easy, interlocking system	5 very easy and fast
Integration	5 compatible with wooden roofs	5 traditionally used	3 needs stable structure	4 flexible, good adaptability
Aesthetic Perception	4 rustic and natural 	5 traditional/ patrimonial value 	3 standard look, gray or red 	4 modern, varied 

This represents the material's secondary use: once its primary function as a roofing element is completed, the tile can be incorporated into the soil, improving its structure and nutrient content.

In dry environments, the original prototype manufactured in 2022 maintained its structural functionality without signs of degradation, suggesting prolonged stability under low humidity and intermittent outdoor exposure. This empirical evidence supports the compound's ability to retain its functional performance as an architectural cover even after extended use, as long as degradation is not triggered by humid conditions.

This behavior suggests that in dry environments with sporadic rainfall (characteristic of the Peruvian highlands) the tile can extend its service life while preserving its structural functionality, without initiating biodegradation processes until environmental conditions become favorable. This stability contributes to its effectiveness as a regenerative architectural solution, combining constructive functionality with agroecological potential to ensure utility in arid zones and progressive compostability in suitable conditions (Fig. 7).

It is important to emphasize that the experimental compound design is entirely free of synthetic additives, solvents, or pollutants, ensuring a safe degradation process without releasing artificial compounds. This attribute classifies the material within the category of compostable biomaterials suitable for reintegration into agroecological cycles.

In this regard, the proposal adheres to the principles of circular economy and regenerative design [20], promoting the natural closure of material cycles within rural and ecological architectural contexts. The qualitative and experimental validation reinforces its potential as an innovative component in low-impact sustainable construction strategies.

Fig. 7: Ecological tile material undergoing degradation after fulfilling its primary function

IV. DISCUSSION

The results obtained indicate that the ecological tile is a viable, accessible, and sustainable solution for Andean rural contexts. Its low environmental impact, ease of production, and adaptability to traditional construction systems position it as a pertinent alternative in the face of climate change and resource scarcity (see Fig. 8).

Despite the operational advantages of commercial polypropylene tiles (such as low specific weight and high moisture resistance) their non-biodegradable nature and petrochemical origin render them environmentally unsustainable in contexts prioritizing resource circularity. Similarly, while clay tiles are culturally rooted in vernacular architecture, their firing process requires high energy input, significantly increasing their environmental footprint.

Fig. 8: Photorealistic simulation of final finish of the tiles in a rural Peruvian highland dwelling.

In this context, the development of technologies with an ecosocial approach is emphasized, understood as technical solutions aligned with the socioterritorial realities of vulnerable communities [21]. Accordingly, the proposed ecological tile is configured as an appropriate, locally-based technology, integrating endogenous resources and community knowledge in the experimental design of constructive compounds, thus promoting resilient and sustainable architecture.

The recognition received at the international invention competition KIWIE (Korea International Women's Invention Exposition), where the proposal was awarded a silver medal, supports the relevance, appeal, and innovative potential of the prototype, validated by expert juries specializing in emerging ecosustainable technologies. This international endorsement provides evidence of the academic and technological interest that the development has generated, reinforcing its feasibility as a replicable solution in contexts facing similar socio-environmental challenges. Furthermore, as of the writing of this article, the ecological tile has a patent application in process, which certifies its novelty, industrial applicability, and potential for technological transfer as a low-impact bioconstruction solution.

V. Conclusion

This study enabled the development of an ecological tile made from organic waste, whose experimental design of constructive compounds and manufacturing process have proven technically and environmentally viable. The resulting material exhibited physical and mechanical properties suitable for use as a roofing system in rural buildings located in high-altitude Andean regions, demonstrating stable morphology during molding, structural resistance after drying, and compatibility with vernacular construction techniques. Additionally, its fully biodegradable composition, low production cost, and the feasibility of artisanal fabrication without industrial machinery facilitate its implementation in highly vulnerable contexts, enhancing the utilization of endogenous resources. These characteristics consolidate its social value as an accessible alternative to conventional construction solutions.

From an environmental standpoint, this proposal aligns with the principles of circular economy and regenerative design, since at the end of its functional life cycle, the material can be reintegrated into the soil without generating contaminating externalities. This feature reinforces its potential as a sustainable construction solution within the context of contemporary ecological architecture.

Experimental findings demonstrated that the compound design successfully integrates structural functionality, technical feasibility, and sustainability criteria. Notably, the incorporation of shortening as a functional additive generates a hydrophobic film on the material's surface, reducing moisture absorption during its service phase. However, upon structural fractures or failure, this protective layer disintegrates, facilitating progressive water infiltration, which activates the transformation of the material into compostable organic fertilizer.

This behavior constitutes both a technical and environmental response to the issue of construction and demolition waste (CDW), by developing a dual-function material: during its active phase as a construction component, and at the end of its life as a soil enhancer. The functional transition between these states occurs without the need for industrial processes, positioning this proposal as a robust example of regenerative design in rural and ecosustainable construction systems.

Although the results are promising, further experimental phases are recommended, including durability testing under controlled environmental conditions, impact resistance evaluation to hydrometeorological events, and technical validations aimed at normative certification. These steps will be crucial for enabling its widespread use in social housing programs and rural infrastructure projects.

In summary, this research represents a concrete case of social biotechnology with an ecosustainable approach, in which local production, low environmental impact, and replicability potential converge to offer a viable technical response to rural housing deficits. Its future integration into public policy could positively influence habitability improvements in vulnerable communities, fostering more resilient, equitable, and ecologically responsible construction practices.

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