

Article

An Exploratory Design Framework for Ceramic Water Filtration: Natural Principles, Vernacular Knowledge, and Digital Fabrication in a Slovenian Case Study

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Abstract

Against the backdrop of the environmental crisis, access to water has become a critical challenge at both global and local scales. In Slovenia, dispersed settlement patterns mean that a significant share of the population relies on small-scale, self-managed, or insufficiently monitored water supply systems. This paper presents an exploratory practice-based case study and develops a design framework that integrates natural processes, vernacular knowledge, and new technology for water-related challenges in unmonitored catchment areas. The framework is articulated through the development of a site-responsive prototype for the Lipnik Spring in Triglav National Park, where elevated *E. coli* levels have been detected. The fabricated component is a 3D-printed ceramic gyroid filtration module, while the proposed system-level concept integrates an Archimedes' screw mechanism to investigate how the kinetic energy of flowing water could support operation without external electricity. The study documents how ecological processes, local material knowledge, and digital fabrication were combined within a sustainability-oriented design process. Contextual iterations in Georgia and France apply the framework's decision-making logic to different environmental conditions and locally available materials. The paper contributes to design practice research and sustainability-oriented prototype development by articulating a structured approach to designing context-specific water-access concepts with low operational energy demand for remote settings.

Keywords: water access; ceramic water filtration; site-responsive design; sustainable product design; vernacular knowledge; low-operational-energy system; 3D clay printing; digital fabrication



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1. Introduction

Climate change is increasingly shaping environmental conditions through more frequent and intense extreme events, including floods, droughts, and wildfires, thereby amplifying pressures on natural resource systems [1]. Within this broader environmental crisis, water systems have emerged as a critical area of concern, as rising global temperatures significantly alter hydrological cycles and aquatic ecosystems [2,3]. Contemporary research indicates that anthropogenic pressures, including overconsumption, pollution, and climate-driven variability, are pushing freshwater systems beyond stable operating conditions [4,5]. The concept of planetary boundaries provides a useful framework for understanding these dynamics, defining a safe operating space within which humanity can continue to develop without destabilizing Earth system processes [6]. Recent assessments

suggest that key components of the freshwater cycle, including both blue water (surface and groundwater) and green water (soil moisture), have already been significantly altered, approaching or exceeding safe limits alongside other critical planetary systems [4]. At the same time, freshwater ecosystems can undergo non-linear change and regime shifts, meaning that their recovery to previous states cannot always be assumed [7]. Access to safe drinking water remains one of the most urgent challenges within this context and is explicitly addressed in the United Nations Sustainable Development Goal 6, which aims to ensure universal and equitable access to safe and affordable drinking water by 2030 [8]. Despite global efforts, approximately 2.1 billion people still lack access to safe water [9], while 4.0 billion experience seasonal water scarcity [10]. Future projections indicate that water-related risks, including shortages and extreme events, will intensify, affecting hundreds of millions of people worldwide by the middle of the century [11]. Although water insecurity is often associated with low-income or climate-vulnerable regions, challenges related to safe drinking water also occur in high-income countries, particularly in rural, remote, and geographically dispersed areas [12]. In such contexts, small-scale water supply systems are more difficult to manage microbiologically, especially where disinfection is absent or inconsistent [13]. Water sources that are perceived as clean may nevertheless be subject to contamination, revealing a gap between perceived and actual water quality [14]. There is also a widespread lack of understanding that the water cycle operates as a global system, in which local pollution can have far-reaching environmental consequences [15]. Existing approaches to small-scale water treatment often rely on energy-intensive processes, complex infrastructure, chemical treatment, or standardized technologies that are not always suited to remote, culturally specific, or environmentally sensitive contexts [16]. This reveals a need for context-sensitive systems designed for low operational energy demand that minimize dependence on external energy inputs or continuous user intervention while integrating local materials, vernacular knowledge, and contemporary fabrication techniques. In this article, low operational energy refers to the design objective of minimizing external energy inputs during the use phase. In the proposed system concept, this objective is pursued through the intended use of the kinetic energy of flowing water, with the aim of avoiding reliance on external electricity during operation. The term does not denote a measured energy balance or comparative life-cycle performance and does not include embodied energy, material processing, firing, fabrication, transport, maintenance, durability, or end-of-life impacts. Vernacular knowledge should not be understood as obsolete; rather, it is approached here as a repository of situated, low-energy design principles that, when combined with contemporary materials science and digital fabrication, can support more sustainable and locally appropriate solutions. Although decentralized water treatment systems have received increasing attention [17], their intersection with design research remains underexplored, particularly in relation to material experimentation and site-responsive development. In this context, design research offers a valuable framework for translating sustainability challenges into tangible, locally grounded solutions operating at the intersection of environmental, material, and social systems. This paper addresses the identified gap through an exploratory practice-based case study focused on Dodola, a low-operational-energy ceramic water filtration prototype for the Lipnik Spring in Triglav National Park, Slovenia. Dodola was originally developed by the design collective Pjorkkala, consisting of Pia Groleger, Žan Girandon, and Luka Pleskovič. Slovenia's hydrogeological diversity, reflected in its springs [18], aquifers, and water catchments, further motivates the development of localized, site-responsive water solutions with low operational energy demand that respond to specific environmental conditions while minimizing disturbance to the surrounding environment. Within this perspective, ceramic filtration is particularly relevant because clay mixed with combustible

organic matter such as sawdust can form a porous filtration structure after firing, while the resulting filter can operate without continuous external energy input [19,20]. Earlier explorations of xylem tissue filtration also demonstrate the potential of natural materials as water-treatment media [21]. However, their practical limitations point to the need for more durable and maintainable alternatives. The present study builds on the original prototype by articulating and examining its underlying design framework in relation to sustainability-oriented, site-responsive product development. The triadic framework integrates Nature, Vernacular Knowledge, and New Technology and was derived through critical reflection on the original design and prototyping process. Two contextual iterations further examine how its decision-making logic changes across sites. The paper does not present a universally transferable methodology or a technically validated water-treatment solution; its contribution lies in documenting how ecological processes, situated material knowledge, and contemporary fabrication technologies were integrated in the development of a context-sensitive, low-operational-energy water-access prototype.

Within this study, sustainability is treated as a design orientation rather than as a verified environmental performance outcome. It refers to design decisions concerned with responsible material use, site responsiveness, repairability, adaptability, and reduced dependence on external energy during operation. Related concepts such as resilience and regeneration extend this perspective. Resilience emphasizes the capacity of systems to absorb disturbances and maintain function, whereas regeneration seeks not only to reduce harm, but also to restore and enhance ecological and social systems [22–25]. In this study, these concepts are treated as complementary; however, the primary emphasis remains on sustainability-oriented, site-responsive design for decentralized water access.

1.1. Local Context: Water Systems in Slovenia

The Slovenian drinking water system includes a large number of small supply areas, many of which serve rural, peripheral, or geographically dispersed populations [14]. These systems are more difficult to manage microbiologically than larger centralized systems, particularly where disinfection is absent, irregular, or manually performed [13]. National monitoring data indicate that 26.9% of water supply areas operate without disinfection, while in an additional 5.9% disinfection is carried out only occasionally or manually [13]. This corresponds to approximately 591,343 people obtaining drinking water from public sources without continuous disinfection. In such contexts, users may rely on additional purification practices, most commonly boiling [14]. However, boiling requires time, energy, and continuous user intervention, making it less suitable for remote, infrastructure-limited, or frequently used outdoor water sources [26].

These issues are particularly relevant in Triglav National Park, where spring water is commonly associated with purity and ecological integrity. Since 2018, regular monitoring of 13 springs in the park has shown generally stable chemical conditions, with occasional presence of nitrates and phosphorus linked to agricultural activity [27]. More critically, elevated levels of *E. coli* have been detected in four springs, in some cases exceeding 182 CFU/100 mL [14]. According to drinking water regulations, the permitted value for *E. coli* is 0 CFU/100 mL, meaning that any detected presence indicates contamination [28].

The Lipnik Spring (Figure 1) was selected as the primary case study site because it brings these issues together in a concentrated and design-relevant form: it is perceived as a clean natural water source, it is used by visitors and local users, it lacks purification infrastructure, and prior measurements indicated microbiological contamination. The site therefore provided an appropriate setting for examining how a decentralized filtration system intended for low operational energy demand could respond to local environmental conditions while minimizing dependence on electricity and continuous manual operation.

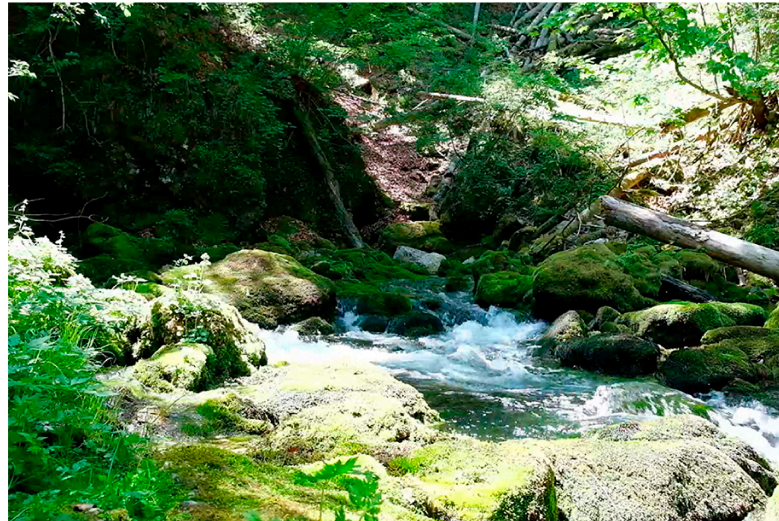


Figure 1. Lipnik Spring in Triglav National Park. Photograph by Pjorkkala (Pia Groleger, Žan Girandon, and Luka Pleskovič), 2022.

1.2. Conceptual Framework: Nature, Vernacular Knowledge, and New Technology

Rather than approaching water purification solely as a technical problem, this research draws on a broader design perspective that integrates environmental, material, and cultural dimensions. In line with critical perspectives on knowledge production, practices such as data collection, organization, and interpretation are not neutral, but actively shape how systems are understood and acted upon [29]. The conceptual framework is structured around three interrelated principles: Nature, Vernacular Knowledge, and New Technology. These were not predefined as abstract categories, but emerged iteratively through the design process and were later formalized as an analytical and methodological structure. The Nature dimension focuses on ecological processes as drivers of design, foregrounding low-operational-energy, material-based processes, including filtration, adsorption, and sedimentation, that operate within existing environmental cycles. Vernacular Knowledge complements this by grounding design decisions in locally embedded material practices and skills, emphasizing accessibility, repairability, and adaptation to specific cultural and environmental contexts. New Technology, in turn, functions as a mediating layer, extending and refining these principles through digital fabrication and parametric design, enabling greater precision, adaptability, and efficiency without detaching the system from its ecological and material foundations. Together, these three dimensions form an integrated framework linking environmental processes, cultural knowledge, and technological innovation within a coherent design methodology.

2. Materials and Methods

This study follows a practice-based design research approach in which knowledge is generated through iterative prototyping, material experimentation, and site-specific application. Building on the local context presented in the previous section, the Lipnik Spring served as the primary case study through which the proposed framework was developed and examined. While the research is grounded in this specific micro-location, the methodological approach may be adaptable to other water environments, with outcomes varying according to local conditions. Two additional exploratory iterations, presented later in the paper, examine how the framework's decision-making logic might be recalibrated across different environmental, cultural, and material contexts. This practice-based mode of inquiry may also be relevant to applied design practice and sustainability-oriented learning contexts [30].

The methodology consists of three stages: (1) research, (2) experimentation, and (3) iteration. The initial research phase involved data collection to understand and define the water environment and local context. The subsequent experimental phase enabled the translation of contextual and material knowledge into prototypes through material testing, fabrication, and iterative evaluation. In the exploratory contextual iteration phase, the developed principles were applied in new contexts to examine the adaptability of the framework.

2.1. Research Phase

With the aim of developing an in-depth understanding of the water environment, ten semi-structured interviews were conducted with experts, users, and Triglav National Park employees. Participants were purposively selected in collaboration with the Slovenian Association for Water Protection, which provided access to professionals with relevant local expertise. All interviews followed a common guide covering key themes, including water-related issues, water use practices, maintenance challenges, seasonal variability, and locally established solutions. The guide was adapted slightly to reflect each participant's professional background. Interviews lasted between 40 and 60 min, were audio-recorded with verbal consent, and subsequently transcribed and anonymized. Transcripts were coded inductively to identify recurring topics, which were grouped into broader themes related to (1) general and local water-related issues, (2) water-related knowledge, (3) water monitoring and treatment, and (4) local hotspots. The interviews provided contextual input for identifying themes and practical questions requiring further investigation. They helped orient the subsequent review of published sources and the prototype-development process, particularly in relation to material availability and durability, maintenance, seasonal variability, and ecological sensitivity within the protected park area.

Participation was voluntary, and the interviews were used only to inform the contextual and design-research dimensions of the study; all contributions were anonymized and are reported without identifying individual participants. In addition to interviews, the study employed a shadowing approach to gain contextual insight. This method was instrumental in site selection, field observation, and the collection of spring water samples in collaboration with a Triglav National Park representative. Three visits were conducted. The first took place in winter 2021, with the aim of identifying a suitable spring for the case study location. The second visit was carried out in spring 2021, during which water samples were collected and the household located next to the spring was contacted. The final visit occurred in summer 2021, when the site was documented and additional water samples were taken. These observations complemented the interviews by helping to contextualize the site and identify environmental and practical questions for further investigation. A market analysis and review of examples of good practice also provided insights into natural purification processes and vernacular practices that remain relevant today.

2.2. Experimental Phase

The research phase was followed by an experimental phase in which two natural water purification techniques were tested: xylem tissue filtration and ceramic filtration. Early prototyping with rapidly produced xylem-based filters revealed significant limitations, as these dried out and clogged quickly. Building on findings by Zereffa and Bekalo [19], initial flow rate observations and preliminary filtration tests were then conducted using ceramic filtration samples. The experimental phase also involved preliminary material trials using simple molds, followed by 3D clay printing. The molded samples were used only to assess the basic workability and drying behavior of the ceramic mixtures and were not included in the subsequent comparative evaluation. Iterative adjustments were

then made to determine a material composition suitable for print stability and firing. Sawdust was incorporated as a combustible organic component intended to generate porosity in the ceramic structure during firing, while grog was initially added to improve dimensional stability and reduce cracking during drying. The clay–sawdust–grog ratios examined during this phase are presented in Table 1. However, the table does not support causal conclusions regarding flow performance, as composition and geometry varied simultaneously across tests. The reported percentages are based on dry weight. The clay used was GWSG-T white earthenware casting-slip powder, manufactured by Sibelco (Westerwald, Germany) and supplied by Töpfereibedarf Ing. Lehrer GesmbH (Leonding, Austria), with a dry shrinkage of 3% and a firing shrinkage of 0.3% at 1000 °C. The sawdust was obtained from the local carpentry workshop Lesna Galanterija Skok Anton (Domžale, Slovenia) and consisted predominantly of untreated solid wood without adhesives. The average particle size of both the grog and sawdust was approximately 0.4 mm. The samples were covered with a thin plastic sheet for the first week to control moisture loss, followed by air drying for an additional week. Drying took place over 14 days in an indoor environment at temperatures between 18 and 22 °C. The samples were fired in a kiln using the following low-temperature firing schedule:

- Segment 1: 60 °C per hour to 150 °C, followed by a 1–2 h hold to allow residual moisture to evaporate safely;
- Segment 2: 100 °C per hour to 600 °C;
- Segment 3: 150–200 °C per hour to 980 °C;
- Segment 4: a 15–30 min hold to equalize the temperature throughout the kiln chamber.
- After firing, the samples were allowed to cool naturally in the closed kiln until they reached room temperature; no active cooling program was applied.

This phase connected material testing with digital fabrication, enabling the development and fabrication of a porous ceramic filter geometry. The resulting design, fabrication decisions, and contextual iterations are reported as results in Section 3.

Table 1. Clay–sawdust–grog mixtures examined during the experimental development of the 3D-printed ceramic filter. Experimental data generated by Pjorkkala (Pia Groleger, Žan Girandon, and Luka Pleskovič), 2022; table compiled by Pia Groleger, 2026.

Parameter	Test 1	Test 2	Test 3	Test 4	Test 5
Clay (%)	80	80	88	88	85
Grog (%)	5	5	2	2	0
Sawdust (%)	15	15	10	10	15
Height (cm)	4	14	5	5	16
Diameter (cm)	18	13	8	10	8
Wall thickness (cm)	1	1.5	1	1	0.5
Water flow (drops/10 s)	1.3	3.3	1.3	0.4	2

During prototype development, exploratory microbiological screening was conducted using a portable Microbium® MPN Analyser for *E. coli* detection and the corresponding MPN reagent (Microbium, Trbovlje, Slovenia). The procedure involved mixing the water sample with the reagent, followed by a 24 h incubation period and colorimetric detection. At the Lipnik Spring, baseline screening indicated the presence of *E. coli*, but transport and processing delays prevented a paired comparison of unfiltered and filtered samples. A second screening was therefore conducted using water from the Gradaščica River, which was located closer to the testing facility; the untreated sample exceeded the device's upper reporting range.

These observations formed part of the iterative prototype-development process and informed the need for more controlled microbiological testing. Because the screening did not generate a complete paired dataset suitable for calculating log reduction, it is not used here to quantify filtration performance or establish drinking-water safety. Overall, the experimental phase connected material testing with digital fabrication and enabled the development of a fabricated porous ceramic prototype component.

2.3. Iteration Phase

The final methodological phase applied the three principles developed through the research and experimental phases in two additional contexts to explore their potential adaptability. The first exploratory contextual iteration, developed in collaboration with the Floating University on the Mtkvari River in Tbilisi, Georgia, examined how the framework might inform design decisions under conditions of severe water pollution and limited site accessibility. The second exploratory contextual iteration, in Cognac, France, explored material localization as a methodological variable, replacing sawdust with regional organic waste, specifically grape pomace and stems generated during cognac production.

These iterations were not intended as direct replications or as technical validations of the Lipnik Spring prototype. Rather, they served as exploratory applications that examined how the decision-making logic of the triadic framework could be recalibrated in response to different environmental conditions, available materials, and cultural contexts. The outcomes of the prototype development and the two exploratory contextual iterations are reported in Section 3.

3. Results: Prototype Development Through Nature, Vernacular Knowledge, and New Technology

This section reports the outcomes of the practice-based development process through the three principles that structured the project: Nature, Vernacular Knowledge, and New Technology. It presents the selection of ceramic filtration following initial xylem experiments, the translation of local material and low operational energy criteria into the Dodola prototype, the fabrication of a 3D-printed gyroid filtration module, and its adaptation in subsequent contexts. The framework is retained as the structure for reporting the results because it guided the design decisions and enables the prototype to be interpreted as a practice-based case of sustainability-oriented product design.

3.1. Nature: Selection of the Passive Filtration Approach

In analyzing existing solutions for treating water contaminated with *E. coli*, mechanical filtration, chlorination, UV purification, boiling, and ozone purification were examined. The analysis of the proposed solutions included not only efficiency and affordability, but also energy demand, maintenance requirements, waste generation, and suitability for remote or infrastructure-limited settings. Conventional filtration technologies often require regular maintenance and replacement of components, which can generate waste, while many systems also require energy inputs that may not be available in remote environments [26]. Chlorine-based purification is effective, but may be less suitable for small rural systems where affordability, dosing, and maintenance are limiting factors [31]. Boiling has also been shown to be an effective method for disinfecting water, but the amount of fuel required is several times greater than that used by a typical family for cooking [32]. Among existing alternatives, UV-based disinfection is a promising option, but depending on the system, it requires either electricity and lamp maintenance or sufficient sunlight [26,33].

The limitations of conventional and high-tech purification systems underscored the need for alternative approaches, directing the research toward natural processes and

traditional knowledge in water filtration. Historically, low-energy methods based on locally available materials have been widely used and adapted to specific environmental conditions [26]. These place-based, nature-driven practices, largely sidelined by modern industrial solutions, formed an essential knowledge foundation for the project. The most common techniques include sand purification, plant purification, charcoal purification, zeolite and limestone purification, bacterial and algal purification, xylem tissue purification (Figure 2), clay purification, and irrigation fields [26]. These practices are grounded in ecological cycles and local materials, aligning with low-impact and sustainability-oriented design thinking. They also prefigure current interest in passively operating, off-grid systems that minimize external inputs and linear resource flows.



Figure 2. Xylem tissue water filtration. Photograph by Bor Cvetko, 2022; reproduced with permission.

Based on this orientation, the project examined natural purification materials relevant to the Triglav National Park context: clay, xylem tissue, charcoal, zeolite, and limestone, all substances that occur naturally in the region or can be sourced with minimal ecological disruption. Charcoal was valued for its ability to remove particles larger than 1 μm and certain chemical pollutants [26]; zeolite and limestone were recognized as natural mineral filters that can absorb metals and adjust water chemistry [26]. Clay, in particular, offered high absorption capacity and low-cost potential, especially when modified through cation-exchange treatments [26]. Xylem tissue filtration, demonstrated in MIT-led studies to block over 99% of *E. coli* while maintaining flow, was also considered as a nature-based model [21]. However, early prototypes based on xylem tissue revealed significant limitations in long-term durability and maintenance, prompting the search for a more robust, locally fabricable alternative. This led to the prioritization of clay as the primary material base, while still drawing on the logic of natural filtration and passive operation with low operational energy demand.

Despite their ecological appeal, natural purification methods are inherently constrained by local conditions and the scale at which they can be applied. They often require specific material availability, longer residence times, and sometimes slower flow rates, which can limit their feasibility in high-demand or emergency settings. In the Lipnik case, the absence of nearby infrastructure and the need for on-site, low-maintenance operation reinforced the importance of combining natural processes with carefully designed physical

structures. The challenge was therefore not simply to adopt a natural solution, but to develop a hybrid design system that retained the ecological benefits of natural processes while improving reliability and throughput.

3.2. Vernacular Knowledge: Material and Operational Decisions

The vernacular design paradigm, articulated by thinkers such as Hassan Fathy and Paul Oliver, emphasizes the use of locally available materials and techniques adapted to specific climates, social needs, and cultural contexts [34,35]. This approach is less about replicating a fixed historical style and more about recognizing traditional ecological knowledge as a living, adaptive system. As Jane Withers writes in the Super Vernaculars context, vernacular traditions are not reactionary or nostalgic, but rather at the intersection of innovation, anthropology and ecology, offering a counterpoint to extractive industrial models and a source of sustainability-oriented design inspiration [36].

In the Slovenian context, vernacular knowledge is closely tied to material heritage and natural resource use. Wood has long been a dominant material, with forests covering more than half the territory and traditional timber-based construction demonstrating advanced understanding of renewable resource management and climatic adaptation [37]. Clay and brick production, present since Roman times, exemplify locality-based material systems that rely on nearby raw materials, established craft knowledge, and relatively simple firing processes [38]. Crafts such as the Ribnica dry-goods tradition further illustrate how vernacular practices embed durability, reparability, and circularity into local economies and social structures [39]. These examples suggest that vernacular traditions are better understood as repositories of ecological intelligence than as static heritage artifacts. They embody principles of circularity, low-energy processing, and long-term resilience that resonate strongly with contemporary sustainability and regenerative design agendas. As Watson (2020) argues, such practices should be recognized as innovative rather than primitive, representing a sophisticated synthesis of knowledge accumulated through generations of experimentation and adaptation [40].

Vernacular knowledge in this project is therefore understood as situated material intelligence embedded in local environments and practices. Vernacular logic is treated as a practical criterion that directly informs key design decisions. Local knowledge functions as a decision-making framework for:

- material selection (prioritizing clay and wood, which are locally available),
- maintenance logic (designing for low-intensity, non-specialist upkeep),
- local feasibility (ensuring the system can be realized and operated with existing infrastructure and skills), and
- repair and replication (supporting cost-efficient maintenance through local knowledge networks).

In the case study, the vernacular principle guided the choice of ceramic filtration as the central purification method. Ceramic filters (Figure 3) are rooted in long-standing vernacular and traditional water treatment practices and remain widely used as low-cost, low-resource solutions in off-grid contexts [41–43]. They are typically produced from locally sourced clay mixed with combustible organic matter (such as sawdust, often 15–20%), then fired at around 980 °C to create a porous structure capable of removing bacteria and sediments [19,20].

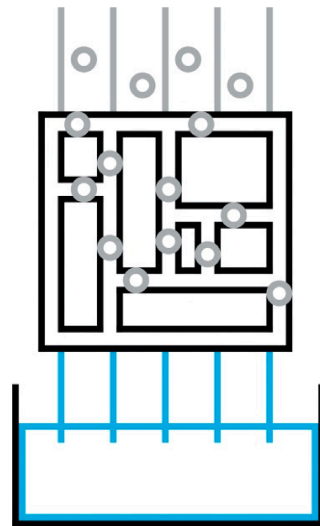


Figure 3. Principle of ceramic water filtration as applied in the development of Dodola. Gray lines represent contaminated water, while gray circles represent impurities retained within the ceramic structure during filtration. Blue lines represent the filtered water. Illustration by Ema Kapelj, 2022; reproduced with permission.

Ceramic filters are well suited to remote, off-grid settings because they require no electricity or chemicals, are durable, and can be maintained with relatively simple local skills [20,44]. Their limitations, such as reduced effectiveness against chemical or viral contaminants [45], are less critical in the specific environmental conditions of Triglav National Park, where no major chemical pollutants were detected [27]. By choosing ceramic filtration, the project aligned with vernacular logics of local material use [43], low operational energy demand [46], and circularity, while also responding to the site's microbiological vulnerability.

The vernacular principle also influenced the decision to integrate hydraulic self-sufficiency into the system. Drawing on the Archimedes' screw, one of the earliest mechanical means of lifting water using flow energy [47], the project explored how water could be moved through the system without external electricity. This conceptual integration was intended to make the design suitable for remote, infrastructure-poor sites where electrical grids or manual pumping are impractical, thus reinforcing the idea of a site-responsive, low-intervention water-access system.

Despite its strengths, a purely vernacular approach can be constrained by material specificity and scalability. In the Lipnik case, reliance on clay-based systems required stable access to appropriate raw materials and firing conditions, which may not be available in all contexts. This limitation points to the need for adaptation rather than replication: vernacular knowledge provides a situated logic for decision-making, but its material expression must change according to local resources, skills, and infrastructures.

3.3. New Technology: Fabrication of the Gyroid Filter

New technology, as conceived here, is not opposed to the principles of Nature or Vernacular Knowledge, but rather positioned as a mediating layer that enables their more effective application. The project engaged with two key technological strands: 3D clay printing and gyroid geometry. The gyroid structure (Figure 4) is an infinite, triply periodic minimal surface that divides space into interwoven labyrinths of channels, effectively increasing internal surface area within a compact volume [48,49]. This geometric property is particularly relevant to filtration, where greater surface area can enhance contact time and potentially support improved removal efficiency.



Figure 4. A gyroid is an infinitely connected triply periodic minimal surface that separates space into two oppositely coherent labyrinths of passages. Photograph by Pjorkkala (Pia Groleger, Žan Girandon, and Luka Pleskovič), 2022.

3D clay printing enables the fabrication of complex internal geometries that are difficult or impossible to achieve with traditional hand-shaping methods. By combining gyroid-based design with ceramic materials, the project exemplifies what Jane Withers' Super Vernaculars concept describes as a respectful advancement of ancestral material practices through contemporary technologies, preserving cultural and ecological roots while enhancing precision, stability, and adaptability. In this context, 3D clay printing is therefore framed not as a purely aesthetic or technological spectacle, but as a contribution to sustainability-oriented design logic. The process supports material efficiency, as the geometry and printing parameters can be optimized to minimize excess clay and avoid over-built sections. It also enables iterative prototyping with minimal waste, since unsuccessful prints can be reclaimed and reused as raw material. Furthermore, 3D clay printing facilitates local and on-demand fabrication, potentially reducing transport emissions and enabling production close to the site of use. The parametric approach allows customization for site-specific hydrological conditions, such as flow rate and water quality, while the modular design of the gyroid filters supports repairability and replaceability of individual components, rather than requiring full system replacement. In this way, digital fabrication is framed as a methodological tool that aligns with principles of circularity, adaptability, and situated material intelligence, rather than contradicting them.

In the case study, the primary limitation of conventional ceramic filters was flow rate and time efficiency. Traditional pot-shaped ceramic filters, while effective at removing bacteria, often suffer from relatively low flow rates, especially when scaled to community-level use. The project therefore sought a structure that could provide a significantly larger internal filtration surface. The gyroid form was identified as a promising solution, enabling water to pass through small, intertwined channels that increase contact area and may improve filtration efficiency depending on material porosity, flow conditions, and maintenance. 3D clay printing was chosen specifically because it allows precise fabrication of the gyroid structure from a clay-organic mixture that is difficult to shape using conventional methods. This technology also supports local, on-demand production and repair, reinforcing the circular and adaptive aspects of the design.

During the experimental phase, the ceramic mixture composition presented in Table 1, together with the clay-to-water ratio and nozzle size, was examined in relation to printability and structural integrity (Figure 5). Because composition, dimensions, and wall

thickness varied simultaneously, the five tests functioned as iterative design trials. Selection therefore relied on an overall design assessment of flow, print stability, structural integrity during drying and firing, expected porosity based on composition, post-firing quality, and compatibility with the printing equipment. Although Test 2 achieved a higher measured flow rate, it showed reduced print stability and lower structural reliability during drying and firing, which limited its suitability for further development. Test 5 was selected because it provided the most workable overall balance across these criteria, rather than the highest measured flow rate alone. Grog was excluded because its particles damaged the printer's metal components. A 3 mm nozzle provided the best balance between resolution and structural stability, while a clay-to-water ratio of 2:1 (by weight) ensured sufficient layer strength without excessive viscosity. The resulting paste was printed at a speed of 150 mm/s and a pressure of 5.5 bar using a Delta WASP 2040 Clay printer (WASP S.r.l., Massa Lombarda, RA, Italy). The gyroid cell size was 1 cm³ at the base. The printed dimensions of the complete object were 15 × 15 × 38 cm before firing shrinkage. The final module was printed in a vertical orientation. The parametric design approach enabled rapid iteration of the filter geometry, allowing the gyroid module to be adapted to different flow conditions and site requirements. This demonstrates how new technology can mediate between abstract theoretical principles and concrete, site-specific needs.

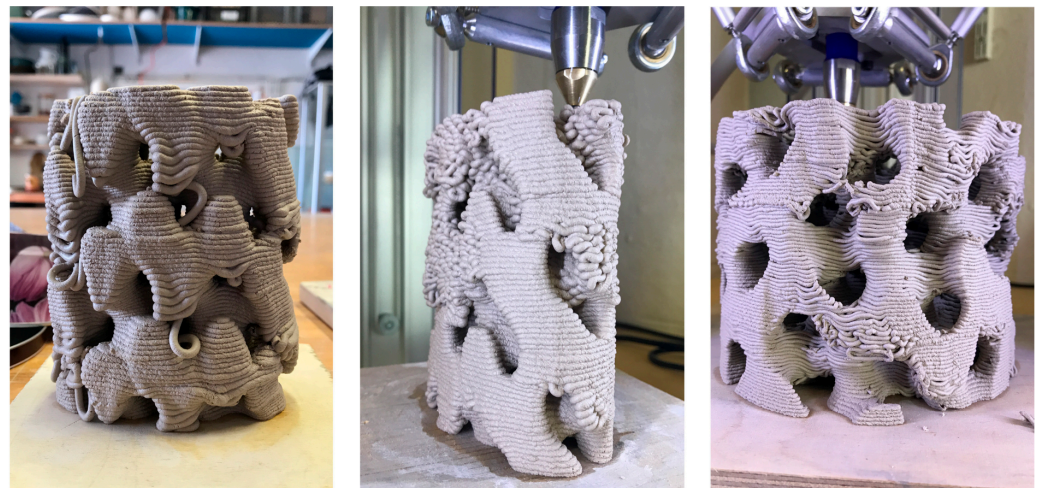


Figure 5. Material and fabrication experiments conducted during the development of Dodola by Pjorkkala (Pia Groleger, Žan Girandon, and Luka Pleskovič): tests with 1.5 mm (**left**), 2.0 mm (**center**), and 3.0 mm (**right**) nozzle sizes. Photographs by Pjorkkala, 2022; reproduced with permission.

Despite its advantages, the use of 3D clay printing and gyroid-based design introduces certain constraints. The process requires access to specialized equipment and technical skills, which may limit immediate transferability to very low-resource contexts. Additionally, the complexity of the geometry can increase the risk of structural failure if material parameters are not carefully controlled. In the case study, the project mitigated these risks through iterative prototyping and close attention to material properties. Furthermore, the high-precision character of parametric design and 3D printing may lead to over-optimization for specific conditions, potentially reducing adaptability in other settings. The project therefore used technology not as a standalone solution, but as a tool to enhance and articulate the underlying natural and vernacular principles, rather than to replace them.

Taken together, the three principles define the design framework not as a fixed recipe, but as a relational method for decision-making. Nature establishes the ecological and process-based logic of purification; Vernacular Knowledge grounds the system in local materials, skills, and maintenance cultures; and New Technology enables precision, iteration, and adaptation. The Lipnik Spring case demonstrates how these principles can be com-

bined in a concrete prototype, while also revealing that their balance must be recalibrated according to site-specific environmental, material, and social conditions.

3.4. Developed Prototype and System Concept

The design and development process resulted in Dodola, a ceramic filtration prototype for the Lipnik Spring in Triglav National Park (Figures 6 and 7). The physically fabricated component consists of a 3D-printed ceramic gyroid filtration module. At the system level, the design concept proposes the integration of an Archimedes' screw mechanism intended to use the kinetic energy of flowing water without reliance on external electricity. The hydraulic integration was not technically validated within the scope of this study. Together, the fabricated ceramic module and the proposed water-driven mechanism illustrate a possible system configuration for a microbiologically vulnerable natural water source.



Figure 6. Dodola filtration module, side view. Designed by Pjorkkala (Pia Groleger, Žan Girandon, and Luka Pleskovič). Photograph by Bor Cvetko, 2022; reproduced with permission.



Figure 7. Dodola filtration module, top view. Designed by Pjorkkala (Pia Groleger, Žan Girandon, and Luka Pleskovič). Photograph by Bor Cvetko, 2022; reproduced with permission.

Figures 8 and 9 visualize the proposed system-level arrangement and intended operating principle. They represent a conceptual configuration rather than a fully assembled hydraulic installation tested under defined operating conditions.



Figure 8. Conceptual arrangement of Dodola filtration modules in flowing water. Designed by Pjorkkala (Pia Groleger, Žan Girandon, and Luka Pleskovič). Visualization by Pjorkkala, 2022; reproduced with permission.

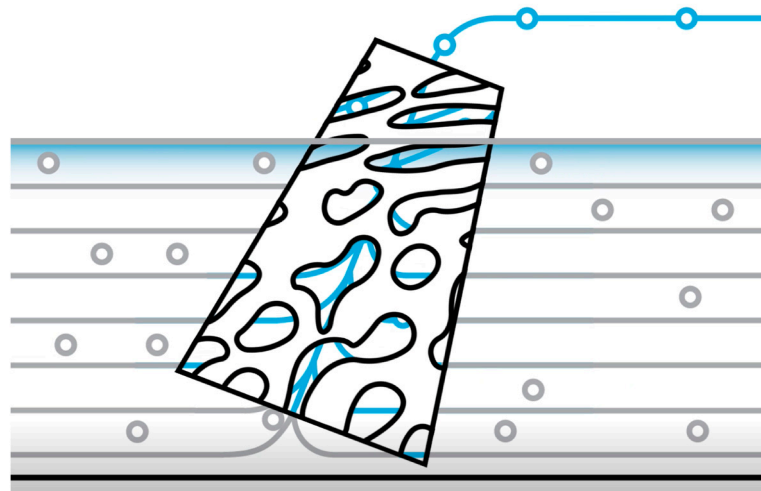


Figure 9. Conceptual operating principle of the proposed system: water is intended to pass through the ceramic filtration module before being transported upward by the proposed water-driven mechanism. Gray lines and circles represent untreated water and suspended impurities, respectively; blue lines indicate the path of filtered water. Designed by Pjorkkala (Pia Groleger, Žan Girandon, and Luka Pleskovič). Illustration by Ema Kapelj, 2022; reproduced with permission.

3.5. Contextual Adaptation and Exploratory Testing Outcomes

Field iterations in Georgia and France examined how the framework's decision-making logic was recalibrated across different environmental, cultural, and material conditions. These iterations were not intended as direct replications or as validation of transferability or technical performance. What was carried forward was not the fixed form of Dodola, but the decision-making logic of the framework.

The Georgia iteration, developed with the Floating University on the Mtkvari River in Tbilisi, Georgia (Figure 10), examined how the framework's decision-making logic could inform design decisions under conditions of severely polluted water and limited site accessibility. Adaptations prioritized deployment feasibility, material configuration, and site responsiveness, while also functioning as a situated probe for discussing water quality and ecosystem vulnerability. In this context, the Nature and New Technology dimensions remained central, while the Vernacular Knowledge dimension had to be reinterpreted in

relation to a different water culture, different pollution conditions, and different forms of site access. The iteration illustrates how the framework’s decision-making logic changes when the environmental and social conditions change.



Figure 10. Installation next to the Mtkvari River. Photograph by Pjorkkala (Pia Groleger, Žan Girandon, and Luka Pleskovič), 2022; reproduced with permission.

The Cognac iteration (Figure 11) explored material localization as a methodological variable, replacing sawdust with regional organic waste, including grape pomace and stems from cognac production. Given that approximately 1 kg of pomace is generated per 6 L of wine produced [50], the study tested its compatibility with ceramic filter production. A single measurement was available for each microbiological indicator ($n = 1$). For indicators with quantifiable paired values, the laboratory report recorded lower counts in the filtered sample. However, because valid unfiltered values for *E. coli* and coliform bacteria were unavailable, some values were reported above or below the laboratory reporting range, replicate measurements were lacking, and method-specific detection and quantification limits were incomplete, reliable reductions cannot be calculated and microbiological safety cannot be assessed. Table 2 is therefore presented as descriptive documentation of exploratory testing rather than as technical validation of filtration performance.

Table 2. Exploratory microbiological measurements of unfiltered and filtered samples collected in Cognac. Analyses performed by the Departmental Analysis Laboratory of Charente, France; table compiled by Pia Groleger, 2026.

Microbiological Indicator	Unfiltered Sample (CFU/100 mL)	Filtered Sample (CFU/100 mL)
<i>Escherichia coli</i>	Not quantifiable *	<1
Coliform bacteria	Not quantifiable *	<1
Enterococci	>80	<1
Aerobic colony count at 22 °C after 68 h	>30,000	100
Aerobic colony count at 36 °C after 44 h	>30,000	100
Spores of sulphite-reducing anaerobes	37	<1

* A valid unfiltered value could not be obtained because interfering flora prevented the isolation and enumeration of colonies. Consequently, the reduction could not be calculated for *E. coli* or coliform bacteria.



Figure 11. Iteration development and bio-waste in Cognac. Photograph by Pjorkkala (Pia Groleger, Žan Girandon, and Luka Pleskovič), 2023; reproduced with permission.

4. Discussion

4.1. From Prototype to Framework

Dodola functions here as a design demonstrator through which the methodological value of the triadic framework is examined; it is not treated as a validated technical response to microbiological contamination at a specific spring. The development of each dimension is traced in the matrix below (Table 3), which links sources of evidence with design insights, criteria, decisions, outcomes, and their respective positions within the triadic framework. The Nature dimension informed the selection of passive, low-operational-energy purification processes; Vernacular Knowledge guided the use of locally meaningful materials, maintenance logics, and off-grid operation; and New Technology enabled the translation of these principles into a 3D-printed ceramic gyroid structure. This framing positions the study's contribution in both prototype development and design methodology. The prototype documents how a local environmental challenge was approached through a structured design process integrating ecological processes, situated material knowledge, and digital fabrication. In this sense, the framework can be understood as providing a way of asking design questions: What natural processes can be activated? Which local materials, skills, and maintenance cultures can support the system? Which technologies can enhance precision and adaptability without overriding ecological and vernacular logics? The framework should be understood as retrospective in its derivation and exploratory in its application, emerging from critical analysis of the documented design process rather than from a controlled comparative study. Its present contribution lies in articulating a structured approach to site-responsive design decision-making, while systematic comparative validation remains a direction for future research.

The Lipnik Spring case clarifies the value of hybridization. A purely nature-based approach was limited by durability and flow-rate constraints, as demonstrated by the early xylem filtration experiments. A purely vernacular approach would have been constrained by conventional ceramic filter forms and production methods. A purely technological approach, meanwhile, could have risked detachment from local material conditions and maintenance realities. The design value of Dodola therefore lies in the negotiated relationship between the three principles, rather than in any one principle taken in isolation.

Table 3. A matrix linking sources of evidence, design insights, criteria, decisions, and outcomes.
Table by Barbara Predan and Pia Groleger, 2026.

Source/Evidence	Design Insight	Design Criteria	Design Decision	Prototype Outcome/ Limitation	Framework Dimension
Field observations at Lipnik Spring: perceived as clean, used by visitors and local users, but microbiologically vulnerable and without purification infrastructure.	The site requires a solution that responds to a specific micro location rather than a standardized infrastructural system.	Site responsiveness; low operational energy; minimal user intervention.	Development of a decentralized filtration prototype for a specific spring context.	Prototype addressed the site as a design case, and supported an exploratory assessment of the proposed filtration principle; however, microbiological safety and long-term field performance remain to be established.	Nature/site-responsive design
Review of conventional water treatment options: boiling, UV, chlorination, mechanical filtration.	Existing solutions may require energy, chemicals, infrastructure, maintenance or continuous user action.	Passive or low-operational-energy process; suitability for remote settings.	Shift toward material-based passive filtration.	Ceramic filtration selected as a promising approach; further testing required for performance claims.	Nature
Initial experiments with xylem filtration.	Xylem offered a nature-based model but was limited by drying, clogging and durability.	Robustness; maintainability; longer-term material stability.	Xylem was abandoned as the primary material route.	Helped define the need for a more durable ceramic-based solution.	Nature
Local material and vernacular traditions: clay, wood, ceramic practices.	Vernacular knowledge can inform material choice, repairability and feasibility without being treated nostalgically.	Local material availability; repairability; low maintenance.	Clay-based ceramic filtration selected; organic matter introduced to generate porosity.	Supports low-resource logic, but depends on clay properties, firing access and local production capacities.	Vernacular Knowledge
Material tests with different clay/sawdust/grog ratios and geometries.	Filtration performance cannot be evaluated only through flow rate; printability, stability, firing quality and porosity also matter.	Balance between flow, print stability, mechanical integrity and post-firing quality.	Test 5 selected, not because it had the highest flow, but because it best balanced printability and structural stability.	Test 5 provided the most workable balance across the stated criteria; however, the individual effects of composition and geometry were not independently controlled.	Vernacular Knowledge/New Technology
3D clay printing and gyroid geometry.	Digital fabrication can extend vernacular ceramic practice by enabling complex internal geometry and iterative adaptation.	Increased surface area; modularity; precision; adaptability.	Development of 3D-printed gyroid ceramic module.	Fabrication of complex ceramic module; not yet full technical validation of filtration or hydraulic operation.	Nature/New Technology

Table 3. *Cont.*

Source/Evidence	Design Insight	Design Criteria	Design Decision	Prototype Outcome/Limitation	Framework Dimension
Archimedes' screw principle	Water movement itself can be considered as an operational resource.	Low operational energy; off-grid operation.	Integration of water-driven movement into the prototype concept.	Conceptually supports autonomous operation, but hydraulic performance data remain limited.	Full triadic framework
Iterations in Georgia and France.	The exploratory iterations carry forward the framework's decision-making logic through adaptation rather than replication. Different sites require different material and operational decisions.	Contextual adaptability; material localization; exploratory comparison.	Georgia: situated probe in polluted river context. France: replacement of sawdust with grape pomace.	Illustrates exploratory contextual translation but does not constitute systematic validation of transferability.	Full triadic framework

4.2. Contextual Adaptation Through Exploratory Contextual Iterations

The contextual iterations reported in Section 3 show how the framework's decision-making logic was recalibrated across different settings, with adaptation rather than replication as the central principle. This distinction is central to the contribution of the paper. A site-responsive design framework cannot be evaluated by asking whether the same object can be reproduced everywhere; it must be evaluated by asking whether its principles can support meaningful decisions under changing local conditions. This understanding of transferability also aligns with comparable sustainability research in which case studies are used to develop broader decision-making methodologies rather than universally replicable technical solutions. Similarly, the present study uses the Lipnik Spring case not as a model to be copied directly, but as a structured example of how design can mediate between local constraints and broader sustainability goals.

4.3. Implications for Sustainability-Oriented Design

The case study can also be interpreted in relation to the United Nations Sustainable Development Goals, particularly SDG 6, SDG 9, SDG 12, and SDG 13 [8]. It illustrates how such goals may be translated into a concrete, situated design process, particularly in contexts where water access, material responsibility, low operational energy demand, and adaptation to changing environmental conditions intersect. The project relates most directly to SDG 6 by proposing a decentralized, non-electrical filtration approach for contexts where conventional infrastructure is limited or absent. At the same time, it can be associated with SDG 9 through its use of digital fabrication as a tool for material precision, modularity, reparability, and contextual adaptation; to SDG 12 through its emphasis on responsible material use and low operational energy; and to SDG 13 through its focus on adaptability under changing environmental conditions. Rather than treating these goals as separate categories, the case illustrates how they may intersect within a single design process.

Taken together, these connections position the case within a broader sustainability-oriented design discourse. Dodola provides a concrete example of how environmental

considerations, material responsibility, technological innovation, and local knowledge can be integrated within a single design process. The project translates global sustainability ambitions into site-responsive design decisions oriented toward low operational energy. In the context of sustainable product design and digitalization, the fabricated prototype shows how parametric geometry and 3D clay printing can translate sustainability criteria into material and fabrication decisions while remaining responsive to local resource availability and maintenance cultures.

4.4. Pedagogical Implications

Although the triadic framework emerged from a practice-based product development process, it also provides a pedagogical structure for sustainability-oriented design education. It offers a way of understanding sustainability as an organizing logic that shapes problem framing, material selection, prototyping, evaluation, and contextual adaptation, rather than as a criterion added at the end of a project [30,51–54]. Its pedagogical value lies in making sustainability decisions tangible and negotiable through the development of a concrete product. In the Dodola case, the framework structures an example process in which an environmental challenge is translated into material choices, fabrication decisions, operational principles, and context-specific adaptations. For design education, this offers a way of moving beyond general sustainability ambitions toward the critical examination of how products are actually developed in response to ecological, cultural, and technological conditions.

The three principles can therefore be used not simply as categories for explaining the completed design, but as prompts within a design process: Nature directs attention to ecological conditions and low operational energy demand; Vernacular Knowledge to local material intelligence, feasibility, and maintenance; and New Technology to the selective use of digital fabrication for precision, iteration, and adaptation. Their value lies in requiring students and practitioners to negotiate between these dimensions rather than treating sustainability, technology, and locality as separate concerns.

The iterations in Slovenia, Georgia, and France extend this pedagogical value by enabling comparative examination of different sites, available materials, environmental pressures, and production possibilities. In this sense, the project offers not only a developed filtration prototype, but also a structured approach through which sustainability-oriented product design can be taught, tested, and critically refined.

4.5. Limitations and Future Development

The prototype-development process and contextual iterations define the current scope of the framework and identify the next requirements for microbiological and hydraulic validation. No quantitative hydraulic performance data were collected for the fully integrated system, including its operating flow conditions and water-lifting capacity. These parameters require controlled testing in future development. Long-term outdoor performance also requires investigation in relation to durability, clogging behavior, maintenance requirements, seasonal hydrological variability, and user interaction.

The performance of any future fully integrated system would also depend on local material properties, firing conditions, hydraulic configuration, and the microbiological and chemical profile of the water source. While ceramic filtration is well suited to bacterial reduction, its effectiveness cannot be assumed across all contaminants, particularly chemical pollutants and viruses. For this reason, future applications of the framework should include site-specific water quality assessment and, where necessary, complementary purification strategies.

A further limitation concerns production. 3D clay printing enables complex geometry, modularity, and material precision, but it also requires access to equipment, technical expertise, and controlled material preparation. Moreover, recent life-cycle assessment of 3D-printed clay components for water treatment indicates that their environmental performance depends on factors such as electricity consumption, system configuration, and the distance from which materials are sourced [55]. Future development should therefore explore how the production process could be adapted through local workshops, shared fabrication infrastructures, or alternative manufacturing methods.

While the prototype is designed to minimize external energy input during operation and to incorporate locally available materials where feasible, these objectives remain qualitative. No full energy balance, life-cycle assessment, durability analysis, or end-of-life evaluation was conducted within the scope of this study. Future work should therefore include quantitative environmental assessment and long-term performance testing to substantiate these aspects.

These limitations define the next stage of development without diminishing the study's present contribution. Dodola is a developed design prototype and methodological case rather than a finalized universal product. Future work should focus on long-term field testing, comparative application in different water environments, and clearer operational criteria for adapting the triadic framework across contexts.

5. Conclusions

This paper presented Dodola, a developed ceramic filtration prototype for the Lipnik Spring in Triglav National Park, within an exploratory practice-based design study. It also articulated the triadic framework that emerged from the prototype-development process. The framework integrates Nature, Vernacular Knowledge, and New Technology and connects ecological processes, situated material knowledge, and digital fabrication within a structured design approach.

The study documents the progression from site research and material experimentation to the fabrication of a 3D-printed ceramic gyroid module. Contextual iterations in Georgia and France then applied the framework's decision-making logic under different environmental, material, and cultural conditions. These iterations do not establish technical transferability; they show how the framework can inform context-specific adaptation rather than direct replication.

The research contributes to sustainability-oriented design by showing how low-operational-energy objectives, local material practices, and contemporary fabrication tools can be negotiated within a concrete prototype-development process. Digital fabrication is positioned not as a replacement for vernacular knowledge, but as a means of extending local and natural logics through precision, modularity, repairability, and adaptation.

The contribution of the study lies both in the developed prototype and in the articulation of a design framework that provides a basis for further technical testing, critical refinement, and pedagogical application in sustainability-oriented design.

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Informed Consent Statement: All interview participants were informed of the purpose of the study when invited to participate and voluntarily agreed to take part. Their contributions were anonymized and are reported only in a non-identifiable form; no identifiable personal data or identifiable quotations are included in the article.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

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