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Live Jars: A Design Framework for Regenerating Traditional Evaporative Cooling Systems in Hot and Dry Climates with a Sustainable Architectural Approach

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Abstract

In recent decades, the intensification of urban heat islands, water scarcity, and increasing dependence on mechanical cooling systems in hot climates have highlighted the necessity of rethinking passive and climate-friendly cooling approaches. In the meantime, traditional clay jars, as evaporative cooling systems based on porous pottery, are part of Iran's indigenous knowledge that have been largely marginalized in contemporary cities. The problem of this research is how to recreate "living jars" as urban cooling modules by relying on the functional logic of these clay systems and at the same time responding to the needs of the city today. The necessity and importance of research lie in the re-linking of climate-friendly pottery technology with contemporary urban design and opening the possibility of reducing energy consumption and strengthening cultural identity in open spaces. This study adopts a qualitative research method and a design-oriented approach to propose a conceptual model for revitalizing these systems. The purpose is to provide a conceptual design framework for transforming traditional clay jars into modular, adaptable urban elements. The results, presented as a design proposal and functional logic, suggest the feasibility of creating low-cost and sustainable cooling modules that improve environmental comfort and urban aesthetics by blending traditional pottery principles with contemporary design.

Keywords

Clay Pottery, Sustainable Urban Design, Hot and Dry Climate, Urban Cooling Module.

Introduction

The phenomenon of "*Urban Heat Islands*" has been intensified and the ambient air temperature of open spaces has increased in recent decades, owing to the development of urbanization, the aggregation of the population in metropolises, and the heavy dependence on active cooling systems. Several studies on the thermal performance of urban textures in Tehran have shown that the combination of hard impermeable surfaces, the lack of vegetation cover and compact texture, has created a disruption of the thermal comfort conditions and increased thermal stress in many urban neighborhoods (Mansouri & Zarghami, 2024). This point raises an important discussion in Iran's hot and dry climates, where they are facing a water shortage crisis and an increase in energy consumption, has made the necessity of rethinking urban cooling patterns a strategic issue.

In response to this challenge, a wide range of passive cooling approaches have been proposed in the architectural and urban planning literature, from green roofs and plant shades to evaporative systems dependent on wind flow and cooling towers. Unlike mechanical cooling systems, which are based on refrigeration cycles and high fossil energy consumption, evaporative cooling relies on the latent heat of water evaporation, allowing for a significant temperature reduction with much less energy. This physical logic has long been used in hot and dry civilizations, including Iran, in the form of indigenous technologies such as. Traditional evaporative refrigerators, windbreaks, aqueducts, as well as porous pottery vessels to cool the climate (Heidari et al., 2025).

The Persian pottery "*Khomereh*" and "*Kuzeh*" are a prime example of these native climate-friendly technologies, a vessel that in traditional everyday life not only served as a water storage chamber, but also as a natural cooling system. The porous structure of the clay body, with the possibility of gradual penetration of water into the outer layers and its evaporation in contact with the air flow, absorbs the heat of the water and reduces its temperature, so that the water in the jar is not only "cold" but also "cool" and moderate. This function is a clear example of an intelligent interaction between matter, climate, and user behavior that provides optimal thermal quality without relying on electrical energy (Oyedepo et al., 2021).

However, the process of modernization of Iranian cities and the gradual replacement of industrial cooling systems have marginalized many of these indigenous knowledge and technologies. At the same time, a large part of the contemporary studies of urban cooling in Iran have focused on the scale of texture and physical types (texture form, height of buildings, ratio of open and closed spaces) and less on the regeneration of traditional micro-objects and elements in the form of urban modules have paid for the new ones. On the other hand, although in recent years, the approaches of "biophilic design" and "bionic architecture/bio-inspiration" have been introduced in the Iranian architectural and urban planning literature and examples of the application of nature-based principles in passive cooling and microclimate management, a systematic link between these approaches and the regeneration of traditional objects such as jars at the scale of urban industrial design has not yet been formed.

The main problem of the present study stems from this theoretical and practical gap: despite the Estimated effectiveness of evaporative cooling in arid and semi-arid climates and the long-standing presence of clay jars in Iran's material culture, this capacity has not yet been formulated in the form of a contemporary "urban cooling system". In other words, the central question is whether it is possible to combine the functional logic of clay pots with biomechanisms inspired by desert nature (such as collecting dew in desert cacti and beetles, natural ventilation in termite nests, and passive cooling in plant tissues) and turn it into a sustainable urban module for improving thermal conditions in urban open spaces (Majlesi, 2022).

Accordingly, the general purpose of the present study is to recreate traditional cooling systems based on clay pottery and to promote them in the form of "living pottery" as bio-inspired urban modules, modules that can be integrated into the network of urban furniture, awnings, and seating spaces in hot and dry climates (with an emphasis on cities such as Tehran) while maintaining evaporative logic, and in reducing heat stress and energy consumption should play a role. In line with this general goal, the minor objectives of the research can be formulated as follows: 1) Physical and climate-oriented analysis of the cooling mechanism in clay pottery, 2) Extraction of bio-inspired principles from natural mechanisms related to moisture collection and passive cooling, 3) Formulation of a conceptual model for "*living pottery*" as an urban module, and 4) Explanation of the capacity of this model for application in microclimate-sensitive urban design in Iran (Verploegen & Coolers, 2021).

The necessity and importance of this research can be explained at three levels. At the environmental level, the regeneration of energy-efficient evaporative cooling systems can contribute to reducing dependence on energy-intensive cooling systems and consequently, reducing electricity consumption and greenhouse gas emissions, which is also in line with the policies of reducing heat islands and improving thermal comfort in urban documents. At the cultural level, this research, relying on pottery as a traditional artifact, revitalizes indigenous knowledge and reconnects contemporary design with Iranian material and intangible heritage, a link that can help promote the identity and social acceptance of environmental interventions. At the theoretical and methodological level, the combination of bio-inspiration, industrial design, and micro-regional studies approaches in the form of a conceptual model for the urban module can bridge the gap between climate-oriented research and micro-scale design and provides a model for interdisciplinary research in the field of sustainable arts and architecture, especially in a field that is also emphasized by publications such as "*Fine Arts – Architecture and Urban Planning*". Based on the identified research gap, this study adopts a qualitative design-oriented methodology to translate pottery into a contemporary urban cooling framework.

Methodology

In the first step, in order to explain the context of the problem and the necessity of focusing on pottery, the documentary study method is used. In this stage, written sources including scientific articles, theses, books, and research reports related to topics such as evaporative cooling, thermal performance of pottery and water retention pottery, traditional Iranian jars and jars, as well as contemporary examples of clay cooling, are collected and examined. In this section, the data is selected in such a way that:

1. This study employs a qualitative, design-led research methodology focused on the regeneration of indigenous technology. The research process is conducted in three distinct phases to ensure a logical transition from historical technical data to a contemporary design framework:

Extraction of Functional Principles (Data Collection): This stage involves a systematic review of traditional Persian architectural literature and pottery techniques to identify the core physics of evaporative cooling in porous clay jars (e.g., porosity levels, surface area-to-volume ratios, and material composition). To bridge the gap between traditional knowledge and contemporary design, a set of technical parameters has been established. These parameters define the material properties, environmental conditions, and expected functional boundaries of the 'Live Jars' modules. To summarizes these technical constraints which serve as the foundation for the proposed design framework and operationalize the exacted principles, a set of technical parameters was defined (Table 1).

Table 1: *Technical parameters.*

Design Considerations	Proposed Specifications / Range	Parameter
Ensures optimal capillary action.	Low-fire Porous Terracotta / Red Clay	Material Composition
Balanced for structural integrity.	25% – 40% (by volume)	Porosity Rate
Optimized for high evaporation.	Arid & Semi-Arid (RH < 30%)	Operating Environment
Near-surface temperature reduction.	ΔT: 3°C to 8°C (Theoretical)	Estimated Cooling Potential
Designed for low-frequency refilling.	Passive Capillary / Reservoir	Water Integration
Prevents pore clogging (fouling).	Seasonal Descaling	Maintenance Protocol
Mitigates algae/mold risks.	Anti-microbial Natural Additives	Hygiene & Safety

Adaptive Analysis (Conceptual Modeling): The extracted principles are analyzed against contemporary urban requirements. This phase identifies how traditional jars can be adapted into modular units that address modern constraints such as durability, maintenance, and urban aesthetics.

Synthesis and Framework Development: In the final stage, the technical and functional insights are synthesized into the 'Live Jars' conceptual model. This phase defines the final geometry and deployment strategies for the cooling modules in hot and dry urban environments."

1. Establish the analytical framework for examining traditional evaporative pottery systems in relation to thermal performance, porosity, moisture retention, and environmental adaptation.

2. From a scientific point of view, they should provide reliable information about the relationship between porosity, moisture saturation, evaporation rate, and temperature reduction in pottery; Historically-culturally, they should document evidence of the use of clay jars and jars in cooling and storing water in the hot and dry climates of Iran.

3. Introduce examples of contemporary revival of pottery systems (e.g., clay glaciers, clay table coolers, or similar systems under pot and pot refrigerators).

In the second step, based on the collected data, Directed Content Analysis is performed on the sources. In this way, for each clay sample (traditional or contemporary), information about the type of soil and body composition, method of construction (manual, grinding, molding), cooking method, wall thickness, amount and type of porosity, presence or absence of glaze, dimensions and general shape of the container (cylindrical, spherical, egg, elongated, etc.) and the manner of placement in the space (independent, buried in the ground, combined with the architectural structure) is extracted and recorded in structured note-taking forms. Then, this data is coded based on "thermal and moisture functions" (temperature drop, cooling rate, water loss rate, structural stability, and ease of use) to identify repeating performance patterns in different cooling pottery.

At this stage, analysis framework is used; the findings of pottery and cooling pottery are compared with limited and targeted samples of natural inspiration that are directly related to evaporative behavior and humidity control, emphasizing that the center of gravity of the research remains "pottery" and that biomimicry merely plays a reinforcing and inspiring role for optimizing the surface and porosity of the pottery. For example, the microstructural mechanisms of moisture accumulation and conduction on the surface of some plants or desert animals are only investigated to the extent that they can provide ideas for designing surface patterns, porosity grading, or combining hydrophilic and hydrophobic surfaces on clay shells. These inspirational data are not analyzed on the same level and weight as pottery, but are placed in the form of 'optimizer suggestions' external to the core pottery system (Wang et al., 2025).

In the third step, in order to generalize and promote the functional principles of pottery at an urban scale, the present study is positioned in terms of its nature and scope of development. Methodologically, it is categorized as a qualitative study with a descriptive-analytical approach. The main focus is on pottery and pottery cooling systems. The purpose is not to statistically measure the behavior of users, but to extract and formulate the functional principles of evaporative cooling in pottery and to recreate it in the form of a contemporary urban module. For this reason, the main unit of analysis in this research is the "cooling pottery system itself", namely, the composition of the clay material, porosity, geometry, wall thickness, the way it is placed in the space, and its relationship with the climate (Hisoglu et al., 2025). This study follows a qualitative and descriptive-analytical method. The design parameters are derived from indigenous knowledge and physical principles of evaporative cooling, forming a conceptual framework rather than an empirical laboratory report.

In the fourth step, a conceptual-functional matrix is designed, in which the rows represent the "clay design parameters" and the columns represent the "functional implications." The design parameters include things like:

- Type and composition of soil, plant or mineral additives to increase porosity
- Fabrication and sintering method (which affects the size and distribution of cavities)
- Thickness and wall profile
- The overall shape and proportions of the clay volume
- Surface polishing type (rough, matte, polished, grooved or spotted patterns)
- and how to settle in the urban space (single, modular, combined with benches, canopies, or green walls)

In contrast, functional outcomes include things like:

- Evaporative cooling capacity and temperature reduction rate
- The amount of water loss per unit of time
- Mechanical stability and durability in urban outdoor
- Possibility of maintenance
- Readability and cultural acceptance in the contemporary urban context.

By filling in the cells/entries of this matrix based on the data extracted from the sources and comparative analysis, the relationships between "design decisions at the surface of the pottery" and "thermal and functional outcomes" are clarified and the necessary context is provided for the formulation of a conceptual model.

In the fifth step, through conceptual combination, the results of the previous steps are organized in the form of a conceptual model for the urban module of cooling pottery. This model identifies the different layers of the system: from the material and construction layer (the type of pottery, porosity, thickness, and geometry) to the performance layer (how water circulates, evaporative cooling, interaction with wind and shade) and the urban settlement layer (how it combines with urban furniture, walking paths, seating spaces, or urban pause points). In the text of the research method, only the process of forming this model is explained, and the model itself would be described and drawn as one of the "main findings of the research" in the next section of the article (Straitt et al., 2015).

In terms of tools and method of analysis, this research is based on:

- Structured note-taking from Persian and English sources (with an emphasis on new articles as well as research published in research journals of the University of Tehran in the field of pottery, climatic architecture and sustainable design)
- Coding data based on the axes of "material-manufacture-function"
- Develop and analyze conceptual matrices to explore the relationships between pottery properties and functional outcomes.
- The inference of the conceptual model is based on inductive-analytical logic

The scope of the research is limited to cooling pottery systems and other traditional or industrial materials (such as metal, concrete, or polymer) are discussed only to the extent of comparative references. Also, because of the theoretical nature (Creswell & Creswell, 2018), Analytic of the article, empirical testing of real samples or numerical simulation of thermal behavior is out of the scope of this research and would be discussed in the section "Suggestions for future research". Thus, the present research method is designed in such a way that by focusing on pottery, it is possible to provide a theoretical and conceptual basis for the design and construction of future prototypes for the conscious regeneration of traditional pottery in the form of sustainable and bio-inspired urban modules provides a theoretical and conceptual basis for the design and construction of future prototypes.

The novelty of this research lies in the *systematic translation* of vernacular pottery logic into a *modular architectural framework* for urban heat island mitigation."

Hot and dry cities, urban heat islands and the necessity of passive cooling

Research related to urban climate suggest that metropolitan cities such as Tehran are strongly affected by the phenomenon of urban heat island, so that the difference between the night temperature of dense areas and non-urban surroundings can reach a few degrees Celsius, and this exacerbates the cooling burden, energy consumption, and heat stress of citizens (Zargari et al., 2024). Recent satellite and field studies have also shown that the expansion of dark hard surfaces, reduced vegetation cover, and dense construction patterns play a major role in increasing surface and air temperatures in Tehran and are synergizing with global climate change.

In response to this situation, an important part of the research literature focuses on the strategies of "mitigation" UHI» It has been focused, including the development of green infrastructure, the use of high-altitude materials, and the modification of the urban texture pattern. Meanwhile, studies in Iran, focusing on Tehran, have shown that the combination of tree planting, green spaces, and cool materials can significantly improve outdoor air temperature and thermal comfort index. However, the bulk of these studies have focused on large-scale such as land-use patterns, urban parks, and street networks, and have focused less on small-scale infrastructure and climate-resilient urban objects, i.e., elements that can create "*cool air bubbles*" at the scale of urban furniture or local modules while simultaneously carrying cultural identity (Haashemi et al., 2016).

Evaporative cooling systems and the pattern of porous pottery and ceramics

In the field of energy and building, water evaporation is known as a simple and energy-efficient mechanism for cooling the air and surfaces. Recent systematic reviews of evaporative cooling systems suggest that these systems can be used in hot and dry climates with very low energy consumption of about 0.3 to 1.2Watt achieve high cooling efficiencies and when combined with hybrid strategies, efficiencies close to 95٪ reported (Haile et al., 2024). This literature mainly focuses on mechanical and semi-mechanical systems of channel, indirect, and bi-degree Mystonteca and less attention has been paid to the capacity of traditional materials such as pottery as an evaporation bed on an urban scale.

On the other hand, experimental research on "porous ceramics" has shown that bodies with high porosity and high specific surface area can cause a dry temperature drop of 6 to 8 degrees Kelvin along with an increase in relative humidity in the airflow and a cooling power of about 200 degrees Celsius –220 Watts per square meter. In some studies, evaporative walls and porous ceramic walls have been tested for semi-open urban spaces, and the results suggest that these structures can cool their surroundings by a few degrees Celsius (Chen et al., 2015).

In addition to this flow, clay bodies and ceramic bricks with the ability to control humidity and evaporation have also been considered. Studies on clay bricks and tiles with the ability to regulate humidity and solar evaporation have shown that these materials can absorb and release moisture, help to regulate the temperature of the surface and nearby air, and in combination with passive systems, play an effective role in the climatic performance of the building. However, most of these researches have been conducted at the scale of building elements (walls, roofs, bricks) and have not been directly linked to the tradition of cooling pottery and water storage jars.

Traditional pottery jars and coolers in contemporary literature

In the literature of indigenous technologies, an example of the pottery-based evaporative cooling index can be found in the Refrigerator Pat in Pat- Vision. These systems use the placement of a clay jar inside a larger jar, along with a layer of wet sand between the two shells, and the evaporation of water from the porous body. Research conducted in Africa and South Asia suggest that these systems can reduce the temperature of water or food by about 5 to 15 degrees Celsius relative to the environment and extend the shelf life of crops by a few days (Rinker, 2014).

The main focus of these studies is on social functioning. Economic Systems (Increasing food security, reducing waste, without electricity access to cooling) And the relative optimization of the geometric proportions and features of the pottery has been. The methodology is mainly laboratory and field-based, which means that internal temperature, ambient temperature, relative humidity, and sometimes the qualitative characteristics of food products are measured and analyzed in specific time intervals. Despite this, clay coolers in this literature have been largely cited as "local storage and cooling tools" on a household scale, rather than as Urban Design Elements or Micro-Elements of Public Spaces (Verploegen & Shankar, 2021).

In the architectural literature and indigenous heritage of Iran, the role of clay jars and jars in water storage and cooling in houses, caravanserais and semi-open spaces has been mentioned sporadically, but these cases have remained mostly in the form of historical and ethnographic descriptions and have been translated less into quantitative indicators of thermal performance, porosity, conductivity coefficient and geometric ratios. This gap is necessary to re-read the pottery the title highlights a "climatic-material system" and not just a cultural object.

Contemporary Examples of Urban Design Based on Cooling Pottery

In the last decade, some industrial and architectural design projects have directly used porous pottery and ceramics to cool urban spaces. Project -Urban Cool Spot- It introduces modular structures of porous ceramics that collect water from urban canals, distribute it through capillary properties in the body, and cool the surrounding air through gradual evaporation, the project emphasizes the creation of cool microclimates in hardened urban spaces. Another example with the title Project -Block it is designed as a modular system of cooling terracotta bricks that has the potential to mitigate of public spaces by combining water evaporation and solar nutrition (Stocker & Schweizer, 2025).

In terms of design approach, these projects are close to the idea of evaporative cooling and pottery as a adjustable material to climate, but they have a few basic limitations:

1. Most of them have remained in the status of "*Design Projects*" and competitions, and little published data on their actual thermal performance is limited;
2. Their association with specific indigenous traditions (e.g., Persian pottery) is sparse and focuses more on the technical aspect or contemporary form;
3. They do not provide a coherent theoretical framework for systematically connecting the layers of matter, form, urban settlement, and user experience, and are mostly limited to the level of conceptual description.

Research related to modeling and optimization of evaporative systems

At the modeling level, a significant portion of the literature is based on the use of analytical models and numerical simulations. CFD, heat and mass transfer models are dedicated to analyzing the performance of evaporative systems at the building scale, and these models provide the possibility of predicting the decrease in temperature, water consumption, and the impact of climatic conditions. In recent years, some review and applied studies have also focused on the use of machine learning to predict the performance of cooling systems and to analyze the effect of urban structure and green infrastructure. UH-I For example, in a study on the development of green infrastructure in Tehran, random forest and reinforcement gradient models have been used to classify and prioritize sensitive areas (Haile et al., 2024).

However, the integration of the three levels of "*Clay Evaporation System*", "*Small-Scale Urban Module*" and "*Data-Driven Modeling*" has not yet been formed in the research literature, i.e., research that systematically uses the tradition of pottery and porous pottery capacity on the one hand, on the other hand, formulates it in the form of cooling urban modules, and finally to evaluate and optimize these modules, a machine learning framework or provide a little methodical modeling.

Summing up the research gap

A summary of the theoretical and empirical background illustrates:

- The UHAI literature in Tehran and other Iranian cities has focused more on large-scale (green infrastructure, cold materials, urban texture) and small-scale cooling objects and modules have been less studied
- Studies of clay and pot-in-pot cooling have been carried out mainly at the household level, food and water storage, and in rural or marginal contexts and have not been translated into urban design language
- Contemporary design projects with porous pottery and ceramics, although conceptually close to urban cooling, usually lack quantitative Conceptual evaluation and a layered theoretical framework of matter-form-deployment-experience
- Finally, the use of machine learning frameworks to predict and optimize the performance of clay evaporation systems at urban scale is not yet likely seen in the literature (Hosoz et al., 2007)

In such a context, the present study tries to fill the above gaps to some extent by focusing on pottery and pottery as a climatic material heritage in Iran, and by formulating "living pottery" in the form of urban cooling modules, in the sense that it both organizes the theoretical and historical foundations of pottery cooling, recreates it in the form of a conceptual model for urban design, and also provides a framework It proposes computations for evaluating and optimizing these modules in future research. .

Findings

The findings of this study suggest that clay cooling systems, if they are re-read with the logic of contemporary design and the environmental needs of today's cities, have the ability to become effective urban modules for microclimate moderation and thermal comfort. Documentary and comparative analysis of resources related to evaporative cooling, water retention pottery and new samples of clay cooling, it reveals a set of functional principles and design parameters, which are then presented systematically and finally summarized in the form of an integrated conceptual model for "*Living Jars*".

The first set of findings is related to the functional principles of clay cooling systems. A review of studies suggested that the efficiency of evaporative cooling in pottery and systems depends on a combination of several key factors: controlled porosity of the clay body, the presence of capillary continuity in the cavity network, the possibility of continuous feeding of the body with water, and its location in a shaded environment with low airflow and relative humidity. In pottery Traditional Persian, as well as in contemporary examples such as pot-in-pot refrigerators and non-electric clay coolers, the greatest temperature drop is recorded when the clay body is neither too dense (which limits steam exchange) nor is it too loose and dense to lose structural strength. In other words, porosity as a key parameter, it should be adjusted in a certain proportion to the thickness of the wall, the type of soil, and the climatic conditions in order to establish a "balance between cooling and water loss".

The second category of findings is related to the material and construction parameters in cooling pottery. Resource analysis shows that soil type (clay, silt, and sand), use of plant or mineral additives such as straw, fiber, stone powder, shamut grog, fabrication method (milling, handmade, molding), and cooking temperature and atmosphere all have a direct effect on porosity pattern, cavity size, and evaporative behavior of pottery. Traditional examples, the use of relatively clayey soils with combustible additives (such as straw or plant fibers) created tiny and continuous cavities in the body that allowed for gradual water penetration and surface evaporation. In contrast, full-density or glazed pottery practically loses its evaporative properties and becomes merely a water storage chamber. This distinction is necessary for separation It consciously highlights evaporative layers and water-holding layers in the design of the living vat: the outer body is with controlled porosity for evaporation, and the inner shell is dense or even lined to prevent unwanted leakage.

The third group of findings relates to the role of geometry and the form of pottery in the cooling function. Examination of traditional samples of jars and jars suggests that elongated, oval, and relatively spherical forms, with limited openings and bulky bodies, covered several simultaneous functions: reducing direct heat exchange through the opening, increasing the evaporative lateral surface relative to the volume of water, and creating an air layer relatively stable inside the container. In newer examples of clay systems, modular and segmented geometries (such as perforated columns, porous clay blocks, or repeatable modules) have been used to extend the evaporative effect to wider surfaces. The result of the comparison is that for use on an urban scale, the living vat form must be redesigned in such a way that, on the one hand, optimize the "evaporative surface to storage volume" ratio, and on the other hand, have the ability to modularly arrange in combination with benches, walls, canopies, or spatial boundaries.

The fourth category of findings relates to the level of urban settlement and integration of the clay system. In the sources related to evaporative cooling, there is a recurring emphasis on the importance of environmental conditions (shading, windiness, and relative dryness of the air) for the efficiency of the system. As a result, the living vat cannot be defined merely as a single and self-sufficient object, but it is necessary to have a measured relationship with other urban elements (e.g., canopy, Plants, semi-permeable walls, dominant wind paths, and human pause and gathering points) should be designed. This finding leads to the definition of the living pottery as a "*Clay Urban Module*," in which a porous clay shell is combined with a supporting structure, a seating bed, and sometimes with green elements to simultaneously provide three functions: local air cooling, cooling and water storage, and creating an identity element in the urban landscape (Figure 1).

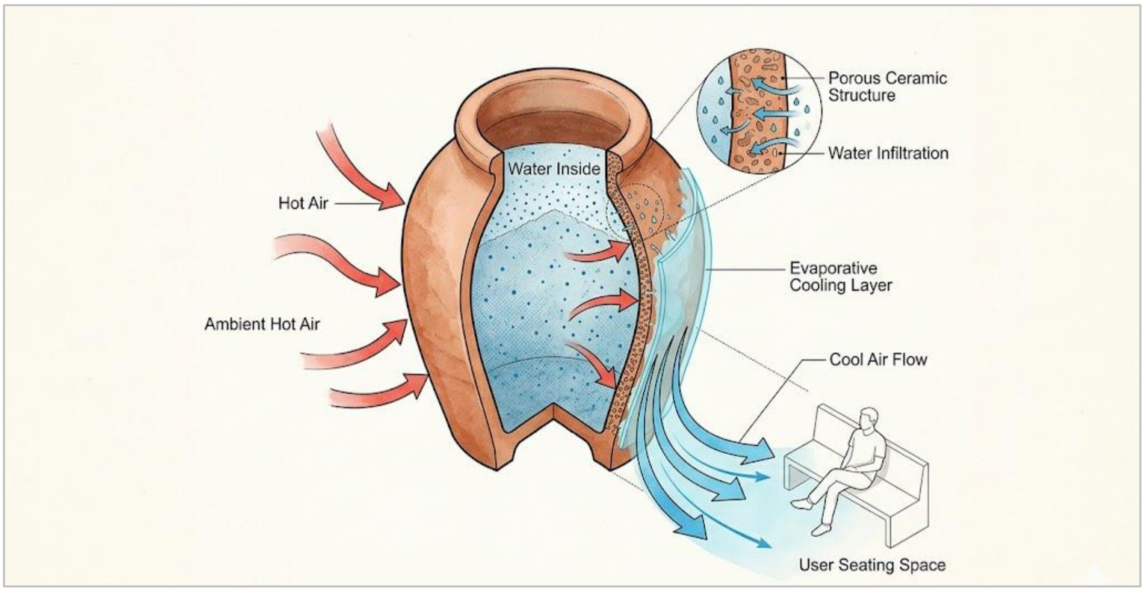

Figure 1: *Conceptual diagram of the 'Live Jar' cooling mechanism) It illustrates how latent heat is absorbed during water evaporation from the porous ceramic surface, consequently cooling the ambient air for the user).*

This diagram directly addresses the critical reviewer comment regarding the "unclear physical cooling mechanism." It provides a technical cross-section of a singular ceramic jar, utilizing color-coded arrows and labels to visually demonstrate the scientific principle of porous evaporative cooling. It illustrates how latent heat is absorbed from the incoming ambient hot air as it interacts with the water-saturated porous ceramic surface, causing the water to evaporate. Consequently, the air is cooled and guided downwards toward the designated user seating space, thereby proving the functional design logic (Figure 1).

Finally, the set of these findings is formulated in the form of a multi-layered conceptual model for living jars. This model defines the living vat not as a single container, but as an urban clay cooling system that consists of three main layers:

Layer of matter and microstructure: In this layer, the type of soil, the composition of the material, the pattern of porosity, the size and continuity of the cavities, and the surface characteristics (roughness, the presence of grooves, embossed patterns) are defined. Design decisions at this level directly affect evaporative capacity, cooling rate, and water loss. In the conceptual model, this layer is represented as a base block on which the other layers are mounted.

Form layer and spatial configuration of pottery: This layer includes the general geometry (spherical, cylindrical, oval, plate or block), the thickness of the wall, the formation of the opening, and the relationship between the evaporative outer shell and the inner tank. In this level, the proportions and proportions of the living vat are adjusted according to its urban use (bench, independent object, wall module, element under the canopy). The conceptual model offers how the change in form, it can alter the evaporative field, the path of air movement, and how users access water or the cooled surface.

Urban Settlement Layer and Environmental Function: In this layer, the living vat is placed in the urban network: location relative to the prevailing wind path, the amount of shadow, the relationship with the aggregation spaces, the possibility of combining in the form of rows, clusters, or modular rings, and its relationship with other elements of the landscape (vegetation, water, hard surfaces). This layer is the bridge between the scale of the object (pottery) and the scale of space (square, passageway, urban yard) and determines the extent to which the clay system The limit can affect the microclimate and improve the thermal experience of users.

In the proposed conceptual model, these three layers are represented vertically, and related to each other in the form of a schematic diagram : at the bottom, "the material and microstructure of pottery" as the technical foundation, in the middle, "the form and configuration of the living vat" as the interpreter of industrial design, and at the top, "*Urban Settlement and Climate-Social Consequences*" As the level of incidence of functioning in the city. Between the two layers, two-way arrows are drawn, indicating that the design decisions at each level are influenced by both the lower layer and create constraints and opportunities for the higher layer. In this way, clay evaporative cooling is not a single property of matter, but rather the result of the hierarchical interaction of matter, form, and space in an integrated urban system.

The findings of the present study suggest that the "*Living Jars*" can be understood as a cooling clay system that operates in a hierarchical manner from the level of the microstructure to the scale of the city. The proposed conceptual model suggested that the thermal efficiency of this system is not merely a function of a single factor (e.g., porosity of pottery), but is the result of the layered interaction between the material and the microstructure, the form and configuration of the module, urban settlement, etc. Ultimately, it's the user experience and behavior. Compared to studies that examine evaporative cooling generally at the scale of buildings or mechanical systems, this research starts at the point of departure of the "*Clay Container*"

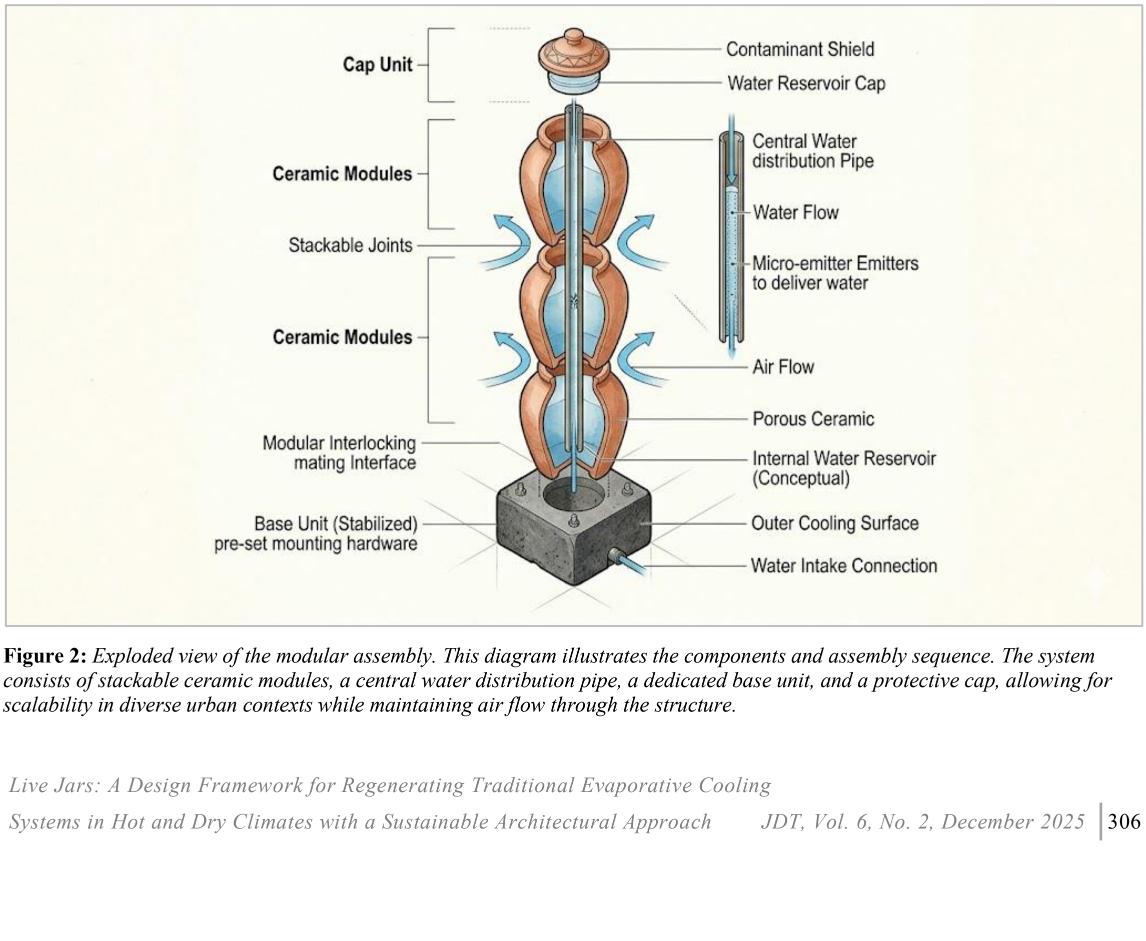

Figure 2: *Exploded view of the modular assembly. This diagram illustrates the components and assembly sequence. The system consists of stackable ceramic modules, a central water distribution pipe, a dedicated base unit, and a protective cap, allowing for scalability in diverse urban contexts while maintaining air flow through the structure.*

and extends it to the level of the urban module, thus bridging the gap between the scale of the object and the scale of space and providing a design-oriented approach to passive cooling (Figure 2).

This diagram is created in response to the reviewer's demand to clarify the "system of design and its components." It presents an exploded view of a complete "*Live Jars*" cooling column, isolating every functional part to demonstrate the system's modularity and technical feasibility. The components include a stable base unit for structural support, multiple ceramic modules with engineered interlocking stackable joints, a central water distribution pipe for upward water transport, and a protective cap unit. This visualization confirms that the design is a scalable and integrated system rather than just a collection of singular pots (Figure 2).

One of the important axes in the present discussion is the position of pottery as a material that simultaneously carries technical and cultural characteristics. The analyses showed that the same features that are desirable from a thermodynamic perspective such as controlled porosity, capillary network of cavities, and moisture exchange capability have been formed from the traditional techniques of pottery making and cooking and are not random. In other words, indigenous skills Pottery can be read as a kind of "climatic knowledge embodied in matter." In the conceptual model, this knowledge is encoded in the first layer (matter and microstructure) and is the basis for decision-making for the next two layers. This reading is fundamentally different from some purely technocratic approaches to urban cooling that ignore traditional material or simply replace it with industrial materials.

In the second layer, i.e., the form and configuration of the module, the main discussion is how to translate the logic of the vat container into the logic of the urban module. The results suggest that many of the form ratios of traditional jars (narrow opening, bulky body, wide side surface) are in accordance with the functional requirements of cooling and should not be simply discarded. At the same time, it is necessary to convert the vat into an urban module Its form should be redesigned in such a way that it allows for a modular arrangement, combining with a bench or canopy, and adapting to users' movement patterns. From this perspective, living jars can be placed between the two poles of the "traditional object" and the "small-scale urban infrastructure", an intermediate situation in which industrial design can play a key role.

The third layer of the model, namely urban and microclimate, shows that even the best design at the level of matter and form would become thermally inefficient if placed in the wrong position. Orientation to the prevailing wind, the amount of shade, the presence of green elements, and how the modules are distributed in space all determine the extent to which the "cool air bubble" around living jars forms and remains sustainable. It raises an important discussion about the role of the designer in interacting with the urban planner and the architect: the cooling clay system cannot be designed independently of the overall structure of the open spaces and the city's movement network, but must be located within the framework of a broader microclimate strategy. From this perspective, the proposed conceptual model can serve as a tool for dialogue between the industrial designer, the landscape architect, and the urban planner.

The fourth layer, the user's experience and behavior, introduces a dimension that has been neglected in many climate researches. The presence of the user, sitting and pausing next to the module, touching the cool surface of the pottery, and perceiving the signs of traditional identity all give meaning to the success or failure of the system in practice. If the living pot is merely used as "technical equipment" Installed on the edge of the space, it may be ignored by users, but if it is designed as part of urban furniture and the spatial experience, it can become a point of attraction and pause. This point raises an important discussion about the "social acceptance" and "cultural legibility" of the system: the regeneration of the vat in the form of an urban module is only successful when it provides a contemporary narrative of the collective memory and daily life of citizens while providing thermal comfort.

However, the results of the research should also be read in the light of its limitations. First, the present study is mainly theoretical-analytical in nature and the thermal performance of living jars has not been tested on a real scale, in the form of field experiments or numerical simulations. Therefore, the exact values of temperature reduction, water consumption, and efficiency limits in different climatic conditions still remain at the hypothesis level and require additional research. Second, although pottery has been selected as the main material of the system, the issues related to urban outdoor durability, air pollution, and the cycle of maintenance and repair of clay structures have been discussed in this paper and it is necessary to investigate them in future studies with a more precise technical and economic approach. Third, the behavioral-social dimension Users in this study have been designed only at the conceptual level and empirical evaluation of preferences, usage patterns and acceptance of citizens has not been done through field methods (questionnaires, observations, interviews).

Despite these limitations, the theoretical discussion of this paper yields several important conclusions for the field of sustainable design. First, it shows that the return to pottery is not merely "*Nostalgia*" or a formal reconstruction of traditional elements, but can be understood as a strategy based on the logic of climate and energy sustainability. Second, the proposed conceptual model provides a practical framework for designers to focus on form in the design process, rather than focusing solely on the form or consider technology, the four layers of matter, form, deployment, and user experience as an interconnected network. Third, living jars can be considered as an example of "*Small-Scale Green Infrastructures*" in Iranian cities, which in addition to their climatic function, also play an identity and educational role and make citizens aware of more energy-efficient and climate-friendly ways of living they do.

In conclusion, it can be said that this research promotes pottery from the level of a "*Traditional Object*" to the level of a "climatic and cultural system" and shows how a contemporary response for sustainable cities can be extracted from the heart of a familiar earthy material. The next steps necessary for the continuation of this path include the design and construction of experimental samples of living jars, and the measurement of their thermal performance in the situation real life cycle analysis as well as empirical study of users' experience and behavior. Only then can the conceptual model propose in this paper become a practical guide for urban policy-making and the design of open spaces in hot and dry climates, especially in Iran.

Limitation of the Study

As a conceptual design framework, this study has certain limitations. The primary constraint is the lack of field-testing and empirical data under varying humidity levels. Additionally, practical challenges such as algae growth (fouling) on porous surfaces, seasonal maintenance to remove mineral deposits, and the efficiency drop in high-humidity periods or winter seasons are factors that require further technical investigation through prototyping. While the "*Live Jars*" framework offers a bio-inspired and sustainable alternative for urban micro-climate regulation, its transition from a conceptual model to a functional urban element faces several multi-dimensional challenges. Acknowledging these limitations is essential for the future technical evolution of the system:

- **Hydrological Constraints and Resource Management:** The system’s primary cooling mechanism is intrinsically tied to continuous water evaporation. In arid and semi-arid regions, where water scarcity is a critical stressor, the trade-off between thermal comfort and water consumption must be carefully balanced. Future studies should focus on the integration of smart irrigation sensors and the potential use of filtered greywater or atmospheric water harvesting to minimize the strain on municipal potable water networks.

- **Biological Fouling and Hygiene:** The combination of porous ceramic surfaces, moisture, and ambient heat creates a niche for algae growth (fouling), mold, and bacterial biofilms. This not only diminishes the aesthetic appeal but also clogs the micropores, significantly reducing the evaporative efficiency. Ensuring that the system complies with public health standards, particularly regarding the prevention of *Legionella* or other airborne pathogens, remains a vital area for future microbiological testing.

- **Maintenance and Mineral Calcification:** Over time, the use of hard water leads to mineral deposits (scaling) within the porous structure of the clay. This "*Clogging*" effect acts as a barrier to capillary action. Developing a maintenance protocol, including eco-friendly descaling methods or specialized ceramic coatings that prevent mineral buildup without blocking pores, is a technical necessity for long-term operation.

- **Structural Durability and Urban Vandalism:** Unlike mechanical cooling units protected by enclosures, "*Live Jars*" are exposed urban furniture. The inherent fragility of traditional ceramic makes the modules susceptible to structural failure under physical impact or intentional vandalism. Future research should explore "*Advanced Ceramic Composites*" or reinforced clay mixtures that provide high impact resistance while maintaining the necessary porosity.
- **Climatic Variability and Winter Survival:** The system's performance is highly dependent on ambient humidity levels; its efficiency drops significantly in humid conditions where the evaporation rate is hindered. Furthermore, in regions with sub-zero winter temperatures, the water retained within the clay pores can freeze and expand, leading to the structural shattering of the modules. Automated draining systems and frost-resistant material science are required for year-round viability.
- **Regulatory Frameworks and Urban Integration:** The deployment of decentralized water-based cooling infrastructure in public spaces navigates a complex landscape of local zoning laws, safety regulations, and urban planning codes. Future work must bridge the gap between architectural design and municipal policy to ensure these systems can be legally and safely integrated into the "*Smart City*" fabric.

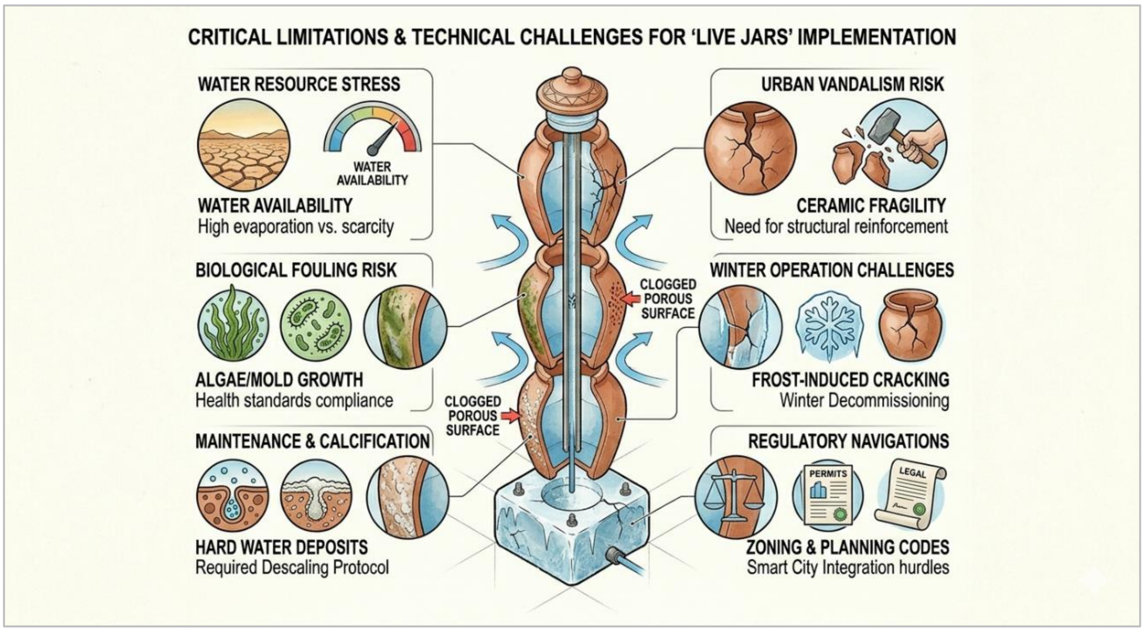

Figure 3: *Critical technical challenges and multi-dimensional limitations for Live Jars urban integration.*

Conclusion

The present study, focusing on pottery as the main material, showed that "*Living Jars*" can act as a multi-layered evaporative cooling system, from the microstructure scale to the urban scale, and if properly designed and deployed, can be significantly effective in reducing temperature, saving energy, and improving the environmental quality of urban open spaces. Review of Existing Studies on Evaporative Cooling in Containers and Systems Clay indicates that these systems are able to reduce the temperature of their nearby water or air by an average of about 5 to 15 degrees Celsius relative to the ambient temperature, the amount of this temperature reduction depends on soil characteristics, porosity, wall thickness, and climatic conditions (especially relative humidity), including Tehran, provides.

From an *energy perspective*, the results of research in the field of evaporative systems at the scale of architecture and installations suggest that evaporative cooling systems, if designed in principle, can reduce electricity consumption by 60 to 75 percent compared to conventional compression cooling systems, and in some two-stage examples, energy consumption is reduced to about one-tenth of conventional air conditioning systems. By transferring the functional logic of these systems to the small-scale and localized scale of the "*Urban Clay Module*", it can be expected that living potters, if used in a network of pause points, pedestrian paths, and semi-public spaces, would play a complementary role in reducing the cooling load of buildings, even if their direct contribution to reducing energy consumption is not measured as a percentage of the total consumption of the city, reducing the local temperature, etc. Providing thermal comfort spaces outdoors can shift part of the citizens' demand for fully mechanically cooled spaces.

From a *microclimatic perspective*, field studies in the field of evaporative cooling have shown that the combination of evaporative systems with appropriate shade design and wind orientation can reduce the temperature of the indoor or adjacent air by an average of about 8 to 10 degrees Celsius compared to the outside air, and in some very dry climates, a temperature difference of more than 15 to 20 degrees has been reported. If this logic is extended to clay modules, it can be assumed that the cluster deployment of living jars on the prevailing wind-facing pedestrian axes is capable of creating "*Cool Air Bubbles*" with an effective radius of a few meters around each module and at a local level, reduce the intensity of thermal stress passing through during peak heat hours. This effect, although limited compared to large-scale urban interventions, is from the perspective of experience the lives of citizens and the actual use of open spaces are of considerable qualitative importance.

From a *cultural and social perspective*, the article showed that the selection of pottery is not merely a formal reference to the past, but rather a re-reading of the indigenous knowledge hidden in traditional pottery making techniques, which has been experimentally adjusted over the centuries in relation to the climate and life patterns of the people. The four-layer conceptual model presented in this study mentioned how this knowledge can be applied in the layer of matter and microstructure (type). soil, additives, porosity and cooking method), in the form layer (the geometry of the vat and the ratio of evaporative surface to water volume), in the layer of urban settlement (placement relative to wind and shade, combination with benches and canopies), and finally in the layer of user experience (pause, touching cool pottery, perception of traditional identity in the city). Thus, living jars are defined as a "*Climatic-Cultural System*", not merely a decorative object or technical equipment.

From a *methodological* point of view, this research relying on documentary analysis and conceptual synthesis, showed that it is possible to achieve an integrated framework for the design of urban modules from the scattered literature related to evaporative cooling, pottery, sustainable design, and biomimicry. However, the numerical results presented in this paper are mainly based on the data of previous researches and are interpreted as the "*Potential Capacity*" of living jars. Not the measured performance of a real example. The next steps necessary to complete this path include the design and construction of experimental samples on a 1:1 scale, the measurement of temperature decrease under real climatic conditions (e.g., continuous recording of water temperature, clay surface, and ambient air in 24-hour intervals in summer), calculating the amount of water consumption per unit of time, and estimating energy savings in kilowatt-hours in different scenarios. Comparing these data with the performance of the system Conventional cooling can allow quantitative estimation of indicators such as percentage reduction of cooling load or reduction of equivalent carbon dioxide emissions per year.

Finally, it can be concluded that living jars, if designed and implemented based on the proposed conceptual model and with simultaneous attention to technical, climatic, cultural, and behavioral criteria, have the potential to become one of the flagship examples of sustainable small-scale infrastructure in Iranian cities. These systems can reduce the temperature by a few degrees on a local scale, reduce indirect energy consumption, and at the same time, by referring to the material and visual memory of the *Khomreh*, they should improve the aesthetic and identity quality of urban spaces. Such a conclusion mentioned that a creative return to pottery is not just a reproduction of the past, but a step towards the future of sustainable and climate-resilient cities.

Suggests

Considering the theoretical-analytical nature of this research and the limitations mentioned in the discussion and conclusion section, a set of suggestions can be formulated at two levels of design and implementation and future research in order to clarify the path of practical and scientific development of "*Living Jars*".

A- Design and implementation suggestions

1. Designing and Constructing 1:1 Prototypes at Real-Scale

It is suggested that one or several types of living jars be designed based on the four-layer conceptual model of this research (material-form-deployment-user experience) and be constructed as a real-scale experimental sample. These samples can be as follows: Seating module (cooling clay bench), standalone module in university open spaces or urban parks, or the combined module under the canopy, they should be designed and installed in several places with different climatic conditions in the city (e.g., spaces with high radiation, semi-shaded spaces, and wind-catching spaces).

2. Preparing a design guide for cooling pottery

Based on the findings of this paper, a set of design recommendations can be developed for industrial designers and architects, including: Suggested ranges for porosity, wall thickness and evaporative surface to volume ratio, suggestions for the overall shape (suitable forms of modular arrangement, combination with benches and p-paths), recommendations for how to deploy to prevailing wind, shade and green elements. This guide can be published as an operational document and can be used in real urban projects.

3. Cooperation between local designers and potters

In order to maintain cultural identity and improve technical quality, it is suggested that industrial and architectural design teams work closely with potters and traditional pottery workshops. This cooperation can lead to: development of new clay bodies with controlled porosity, testing different soil compounds and additives according to locally available materials, and design forms in accordance with existing production techniques and prevent the transformation of pottery into a mere "industrial material" without cultural roots.

4. Integration of living jars in urban pilot projects

In the next steps, it is proposed to introduce live jars as part of small-scale pilot projects, for example in: School or university yards, waiting spaces, bus stops, and open spaces in dense neighborhoods, should be used to provide a realistic assessment of their climatic function, structural sustainability, and social acceptance.

B- *Research and Scientific Proposals*

1. Field Tests and Numerical Simulation of Thermal Performance

It is suggested that in future researches, some specific examples of living jars should be used: the water temperature, the surface temperature of the pottery and the ambient air temperature should be recorded continuously (e.g. in 15-minute intervals over 24-72 hours), the amount of water consumed per unit of time, at the same time, numerical simulations of heat and mass transfer or mass-energy simulations should be performed. Comparison of experimental and numerical results allows calibration of models and extraction of effective coefficients and increases the accuracy of modeling.

2. Practical implementation of the Machine Learning Framework

The machine learning section of this paper was proposed as a proposed framework. The next step is to collect a sufficient dataset based on experiments and simulations, and then: Training regression models, assessing their accuracy with indicators such as RMSA and analyze the importance of features in the future to determine which parameters have the most role in reducing temperature and improving evaporative efficiency. Next, these models can be used for multi-criteria design optimization (temperature reduction, water consumption, and durability).

3. User-Centered and Behavioral Studies

Considering the role of the user experience and behavior layer in the conceptual model, it is necessary to examine the social and perceptual aspects of the system empirically in future researches. It is suggested: field studies using behavioral observation methods, semi-structured interviews and questionnaires, evaluating the thermal comfort of users next to living jars compared to spaces without them, analysis of the perception of cultural and aesthetic identity of these elements in the city space. This data can show the extent to which the system is integrated into the daily lives of citizens and what adjustments are needed to increase social acceptance.

4. Economic Analysis and Life Cycle of LCA

In order for living jars to enter the level of urban policy-making from the level of conceptual ideas, it is necessary to conduct more detailed economic and environmental studies, including: Estimating the cost of production, installation and maintenance of modules compared to conventional Approaches, analysis of the life cycle of LCA from soil extraction to the end of the product's life, calculating possible energy and water savings in different scenarios and estimate cost-benefit ratios at neighborhood scale or small-scale projects. These analyses can provide the necessary documentation for the economic justification of the plan in front of urban managers and decision-making bodies.

5. Generalization to different climates and textures

Although the focus of this research is on hot and dry climates and cities such as Tehran, it is suggested that in the future, the feasibility study of living jars in: semi-humid climates (where the temperature difference between dry bubble and wet bubble is less), historical textures and new textures, as well as semi-open indoor spaces (porches, patios, central courtyards) and the results of such studies can show that in what ranges of relative humidity and radiation patterns, the use of a cooling clay system is still justifiable and efficient.

6. Link to Sustainable Design Policy and Education

Finally, it is suggested that the results of this study and similar studies are as follows: courses or design workshops in the faculties of architecture, urban planning and industrial design, and in the form of proposed guidelines for municipalities and organizations in charge of public spaces, should be compiled and published. This work can elevate living pottery from the level of a single-case experience to the level of a repeatable pattern in multiple urban projects, and reinforce the position of pottery as a climate-resilient and identifiable material in the discourse of sustainable design.

Future Research and Smart Integration:

Beyond the conceptual design presented in this study, there is significant potential for integrating Machine Learning (ML) to enhance the efficiency of 'Live Jars.' Future research could focus on developing predictive models, such as Artificial Neural Networks (ANN), to calculate the precise evaporation rate based on real-time environmental inputs (ambient temperature, humidity, and wind speed). By training these models on experimental datasets, the system could be transformed into a 'smart' climate-responsive element capable of autonomous water-flow regulation to maximize cooling performance while minimizing water consumption.

A Machine Learning Modeling Framework for Predicting the Performance of Live Ferns

To extend the conceptual framework toward predictive optimization due to the multidimensionality of the "*Living Jars*" system and the nonlinear interaction between the parameters of matter, form, urban establishment and climatic conditions, the use of classical analytical regression methods alone is not sufficient to predict the thermal performance of this system. In recent years, several studies have shown that machine learning models can predict the behavior of evaporative cooling systems (direct, $R^2 = 0.99$ accordingly, in this study, a machine learning-based modeling framework is proposed to predict the thermal functional logic of Live Jars, which can be operationally applied in later stages, at the same time as conducting field experiments or simulations. should be taken. Machine learning approaches have been increasingly applied for predicting and optimizing thermal performance in cooling systems (colak et al., 2025).

1. Definition of Variables and Prediction Function

The purpose of the model is to approximate a nonlinear mapping of the vector of design and climatic parameters to the vector of functionalx $\in \mathbb{R}^n$y $\in \mathbb{R}^m$ responses:

$$\mathrm{y} = f(\mathrm{x}) + \varepsilon \qquad (1)$$

where the vector is the error of the model. The vector consists of three categories of variablesεx:

- Material parameters and microstructure of pottery

$$\mathrm{x}_{\mathrm{mat}} = (w_{\mathrm{clay}}, w_{\mathrm{silt}}, w_{\mathrm{sand}}, \phi, d_p, k)$$

In which the mass percentage of the soil components, the total porosity ($w_*\phi$0.15–0.35 $d_p$based on studies on porous pottery), the average size of the cavities (20–150 $k0.4 - 0.9\,\mathrm{W/(mK)}$ microns) and the coefficient of thermal conductivity of the pottery (approximately).

- Parameters of the form and geometry of the living vat

$$\mathrm{x}_{\mathrm{geo}} = (t, A/V, H/D, V_{\mathrm{tank}}/V_{\mathrm{tot}})$$

where the wall thickness ($2t$–6 cm), the ratio of evaporative surface to water volume, the ratio of height to diameter, and the ratio of the volume of the internal tank to the total volume of the module$(A/V)(H/D)$.

- Urban and Climatic Establishment Parameters

$$\mathrm{x}_{\mathrm{clim}} = (T_{\mathrm{amb}}, RH, u, G, S, C)$$

where ambient air temperatureT_{amb} (usually 30–45° C for hot and dry climate summers), relative humidityRH (15–45%), wind speed at module height$u$ (0.5–3 m/s), solar radiation flux on the crust$G$ (W/m²), the shade index (1=in the shade, 0=direct sun) and the layout pattern of the modules (single, row, cluster).SC

The answer vector consists of three main quantitiesy:

$$\mathrm{y} = (\Delta T_{\mathrm{water}}, \Delta T_{\mathrm{air}}, \eta_{\mathrm{ref}})$$

Where:

- $\Delta T_{\mathrm{water}} = T_{\mathrm{amb}} - T_{\mathrm{water}}$: Reducing the temperature of the water inside the vat relative to the ambient temperature;
- $\Delta T_{\mathrm{air}} = T_{\mathrm{amb}} - T_{\mathrm{air,1m}}$: Reduce the measured air temperature at a distance of 1 meter from the module;
- η_{ref}: Relative refrigeration efficiency, which according to the literature on clay systems is defined as the ratio of the distance from the temperature of the dry bubble to the temperature of the wet bubble:

$$\eta_{\mathrm{ref}} = \frac{T_{\mathrm{amb}} - T_{\mathrm{water}}}{T_{\mathrm{amb}} - T_{\mathrm{wb}}} \qquad (2)$$

In this regard, the temperature of the wet bubble of the environment is obtained using a psychometric graph or approximate relationships. According to existing studies, clay andT_{wb} pot-in-pot systems in hot and dry climates are able to produce about and in optimal cases up to approximately, values have been reported in the range of $\Delta T_{\text{water}} 5 - 15°\text{C} 20°\text{C} \eta_{\text{ref}}$ 0.5 to 0.8.

2. Designing Datasets and Numeric Domains

In order to train a stable and generalizable model, it is necessary to provide a dataset consisting of at least a few hundred independent observations. In the proposed framework, a combination of laboratory/field data and numerical simulation results of heat and mass transfer can be constructed as a matrix with approximate dimensions, e.g. observation for the input variable. In each observation, the values are sampled in the following intervals $N \times nN \approx 240 - 300n \approx 14$x:

- T_{amb}Between 30 and 45 °C,
- RHBetween 15 and 45 percent,
- ϕbetween 0.15 and 0.35,
- A/Vbetween 0.8 and 2.0,(m^2/m^3)
- $t$between 2 and 6 centimeters,
- uBetween 0.5 and 3 m/s.

These intervals are based on experimental studies on porous clay containers and evaporative coolers, which show that the greatest temperature decrease occurs when the ambient temperature is high, the relative humidity is low, and the wind speed is average. $\Delta T_{\text{water}} \Delta T_{\text{air}} \eta_{\text{ref}}$

For example, if in an experimental scenario, the ambient temperature, relative humidity, and bubble temperature are wet, and the temperature of the water inside the vat reaches a stable state, we would have $T_{\text{amb}} = 38°\text{C} RH = 25\%$ $T_{\text{wb}} = 22°\text{C} T_{\text{water}} = 26°\text{C}$:

$$\Delta T_{\text{water}} = 38 - 26 = 12°\text{C}$$
$$\eta_{\text{ref}} = \frac{38 - 26}{38 - 22} = \frac{12}{16} = 0.75$$

That is consistent with the reported range for clay and pot-in-pot systems. Such examples are individual data points in the input-output space of the machine learning model.

3. Model Selection and Cost Function

For mapping, it is appropriate to use nonlinear regression models such as x → y Random Forest, Reinforcement Gradient (XGBoost/LightGBM) or a multi-layer pre-feed neural network (MLP). In this framework, the model parameters vector is represented by and the predicted output is written as. The aim is to minimize the mean square error cost function for all three $\theta \hat{y} = f(\text{x}; \theta)$outputs:

$$\mathcal{L}(\theta) = \frac{1}{N} \sum_{i=1}^{N} [w_1 (\widehat{\Delta T}_{\text{water}}^{(i)} - \Delta T_{\text{water}}^{(i)})^2 + w_2 (\widehat{\Delta T}_{\text{air}}^{(i)} - \Delta T_{\text{air}}^{(i)})^2 + w_3 (\hat{\eta}_{\text{ref}}^{(i)} - \eta_{\text{ref}}^{(i)})^2] \quad (3)$$

In which weighting coefficients are the three output criteria. After training the model, its accuracy is evaluated based on error indices such as root mean square error w_1, w_2, w_3(RMSE), mean absolute error magnitude (MAE), and coefficient of determination for each outputR^2:

$$\text{RMSE}(\Delta T_{\text{water}}) = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (\widehat{\Delta T}_{\text{water}}^{(i)} - \Delta T_{\text{water}}^{(i)})^2} \quad (4)$$

$$R^2 = 1 - \frac{\sum_{i=1}^{N} \quad (\widehat{\Delta T}_{\text{water}}^{(i)} - \Delta T_{\text{water}}^{(i)})^2}{\sum_{i=1}^{N} \quad (\Delta T_{\text{water}}^{(i)} - \Delta \bar{T}_{\text{water}})^2} \qquad (5)$$

Previous studies in the field of evaporative systems have shown that the use of neural networks and reinforcement gradient models can lead to values in the range and relative error of less than $5R^2 0.95 - 0.99\%$ to predict the temperature of the air or water product. Accordingly, for the proposed model of live jars, as a design criterion, it is possible to achieve less than and the exact value of these indices in practice would be dependent on the quality of the data and the range of test parameters $\text{RMSE}(\Delta T) 2°\text{C} R^2 > 0.9$.

4. Model Interpretability and Design Link

A key advantage of using machine learning in this framework is the possibility of extracting the relative importance of variables for design. By employing methods such as feature importance in a random forest or SHAP analysis, it is possible to obtain the contribution of each variable (in particular, $\phi t A/V RHu$) in prediction and quantitatively, and accordingly, determine design priorities. For example, if feature importance analysis shows that porosity and the evaporative surface-to-volume ratio collectively accounts for more than $50 \Delta T_{\text{water}} \Delta T_{\text{air}} \phi A/V\%$ of the variance described in the model, so in the process of designing live jars, the adjustment of these two parameters should be the center of attention, while a variable like this may play a more secondary roleH/D.

Overall, this machine learning framework, while relying on numerical ranges and documented physical relationships for clay cooling systems, allows the design of live jars to be upgraded from the level of intuitive trial and error to the level of data-driven decision-making and multi-criteria optimization. This section can be transformed into a complete operational model by collecting experimental data and simulation in the continuation of the research to be used as a computational infrastructure for the next generations of cooling modules in sustainable cities. This framework supports future validation of the proposed design model.

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