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Evaluation of Tawa Khana as a vernacular floor heating system for enhancing building energy efficiency: A case study of Kabul City, Afghanistan

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ABSTRACT

This study investigates the potential of Tawa Khana, a vernacular heating system used in Asian countries, particularly Afghanistan, to improve building energy efficiency. Tawa Khana utilizes radiant floor heating, drawing warmth from a cooking stove or fireplace to heat the floor and subsequently the room. However, it is neglected in contemporary designs, and there is a predicted risk of losing this valuable knowledge entirely within the next few decades. This study aims to evaluate Tawa Khana's features, including its design and construction methods, with the goal of establishing a design manual for Tawa Khana. Furthermore, it analyzes the multifaceted contributions of Tawa Khana to building energy efficiency. For this purpose, a case study evaluation with comprehensive simulations analysis through the DesignBuilder program was conducted. The results indicate that Tawa Khana is applicable with minimal additional technology, increasing room temperature by 4 degrees Celsius, demonstrating its effectiveness as a sustainable heating strategy. This vernacular technique efficiently utilizes waste heat from cooking activities, reducing reliance on conventional heating systems and promoting energy conservation.

1. Introduction

The relationship between architecture and the environment is intrinsically intertwined, mirroring the interconnectedness of humans and nature. Vernacular architecture exemplifies this dynamic interaction across various cultures [1]. However, the construction sector raises significant concerns in contemporary society due to human activities like deforestation, land-use changes, urbanization, and building development [2]. With nearly half of the global population residing in urban areas [3], the building sector emerges as a critical contributor to resource consumption, energy use, and greenhouse gas (GHG) emissions [4]. Studies indicate that buildings account for approximately 40% of resource utilization, 30% of total energy consumption, and 30% of global carbon emissions [5–10]. Air pollution represents a pressing challenge, particularly in Kabul, the capital of Afghanistan [11]. This problem primarily stems from urban expansion and energy consumption within buildings, with pollutants like NO_2, SO_2, and CO being the most significant concerns. Kabul's poor air quality and overpopulation place it among the world's most polluted cities, alongside metropolises like New Delhi and Beijing [11]. Research suggests that coal power generation, wood and gas burning, and biomass use for heating during winters are the main sources of these pollutants in Kabul [12]. The concentration of NO_2, CO, and SO_2 in the troposphere demonstrably decreases from winter to summer. Existing data indicates that Kabul's residential buildings rely on electricity and natural gas for energy during warmer seasons, while colder months necessitate wood, coal, charcoal, and natural gas [13]. Furthermore, rapid urbanization and the construction of buildings that deviate from established standards contribute to environmental degradation and resource depletion [14]. In conclusion, implementing energy-efficient strategies in building design and construction, along with comprehensive integration of renewable energy sources, presents a viable solution to reduce air pollution levels associated with energy consumption [15].

In contrast, vernacular architecture prioritizes the efficient utilization of minimal resources and energy,

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while simultaneously serving as an embodiment of cultural and social values. Research suggests that neglecting the principles and resources employed in vernacular architecture poses a significant challenge in addressing contemporary urban housing issues [16]. Modern buildings are responsible for a substantial portion of global energy consumption and greenhouse gas emissions, exceeding 40% and 30% respectively [17]. When compared to modern designs, vernacular architecture demonstrates a greater degree of environmental adaptability due to principles honed over generations [17]. Multiple studies conducted across diverse regions and time periods have consistently corroborated the energy efficiency and sustainability of vernacular architectural techniques [18]. Notably, the past decade has witnessed a surge in interest towards vernacular design principles for heating and cooling purposes, aligning with the growing movement of energy-efficient architecture [19]. However, despite this recent upsurge in interest [20], the comprehensive potential and benefits of vernacular architecture remain underrecognized and insufficiently integrated into modern design practices.

Currently, Kabul residences experience a significant increase in energy consumption during winter due to reliance on coal and wood for space heating [12]. Wood, charcoal, and coal remain the primary heating sources for homes throughout Kabul's cold seasons. Therefore, incorporating vernacular design principles into building practices becomes crucial for reducing energy demand, particularly during winters. However, contemporary building design in Kabul City often fails to capitalize on these energy-efficient vernacular strategies. Traditional Afghanistan's techniques, often implemented in their basic form for rural dwellings, are rarely incorporated or entirely disregarded in most urban constructions, particularly in Kabul. This trend is particularly concerning for Tawa Khana, a vernacular heating system. Its application is diminishing even in rural areas due to its exclusion from contemporary design practices. The continued neglect of Tawa Khana in contemporary architecture, coupled with a lack of research on its adaptation for modern buildings, suggests a potential risk of losing this valuable knowledge entirely within the next few decades. Existing studies on Tawa Khana primarily focus on its discussion rather than providing substantial information about its design methods and contributions to reducing building energy demand [21,22].

This research delves into the potential of Tawa Khana, a traditional Afghanistan's heating system. By thoroughly evaluating its thermal efficiency and design principles, the study aims to breathe new life into this neglected energy-saving technique. The study seeks to establish a replicable design manual for Tawa Khana, promoting its use in contemporary building practices to enhance energy efficiency. Furthermore, the research will utilize comparative simulations to showcase the applicability and energy-saving benefits of Tawa Khana within Kabul's building design.

This research significantly contributes to the existing body of knowledge on Tawa Khana as a vernacular technique that effectively utilizes waste heat from cooking to reduce reliance on traditional heating systems, thereby promoting energy conservation. Furthermore, the study revitalizes this valuable cultural heritage by providing a detailed manual for the design and construction of this strategic system. Through rigorous investigation, the study unveils the diverse benefits of Tawa Khana for sustainable building design. Ultimately, this research offers a practical framework for architects and policymakers to integrate this approach into their designs and policies, thereby significantly enhancing building energy efficiency.

2. Material and Methods

Vernacular design solutions have historically adapted to specific environments and purposes, often employing a variety of techniques to achieve thermal comfort throughout the year, providing warmth during winters and coolness during summers [23]. This body of knowledge represents a valuable resource, accumulated over generations, that offers valuable lessons for contemporary architecture [24]. Notably, vernacular architecture prioritizes passive environmental control techniques, demonstrably achieving high levels of energy efficiency [24]. These techniques encompass maximizing natural ventilation, incorporating insulation, strategically utilizing shading, and employing thermal mass for heat storage and release. Within the context of this study, Tawa Khana (Ondol) is identified as the most prominent vernacular strategy for building heating. To analyze its contribution to building heating demand, DesignBuilder, a well-established building energy modeling tool, will be employed.

2.1. Tawa Khana (Ondol)

Tawa Khana (Ondol) exemplifies its environmental commitment through its promotion of energy efficiency and its sensitivity to site-specific factors. This vernacular heating system, primarily found in Afghanistan, shares similarities with other historical approaches. Notably, the Korean Ondol floor heating system, dating back to 400 B.C., also utilizes a fire pocket for both cooking and heating, promoting energy efficiency [25]. Furthermore, Anatolian Seljuk architecture employed a similar central heating method, where smoke from a hypocaust (an underfloor heating system) in a nearby bath traveled through terracotta pipes laid underground, distributing heat throughout connected rooms [26]. These historical examples demonstrate the cross-cultural application of similar principles for efficient space heating.

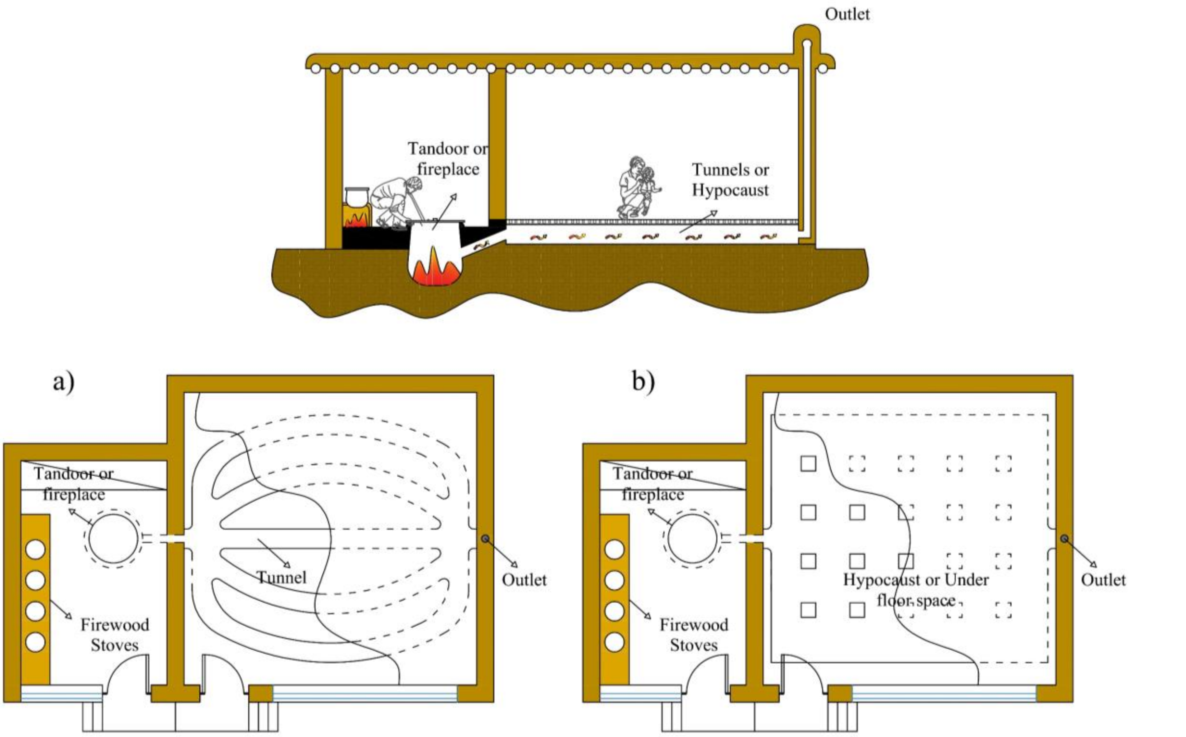

Figure 1. Plan and cross-section of a living space and kitchen featuring a Tawa Khana (Ondol), a) Tawa Khana featured tunnel structures, b) Tawa Khana featured hypocaust structures.

Tawa Khana functions as a radiant heating system. The heat source originates from a clay oven, known as the Tandoor, typically situated in the kitchen. This primary heat source can be supplemented by stoves, ovens, wood, or charcoal heaters located either within the kitchen or externally. As the heat source is used, particularly during cooking processes, residual warmth is circulated through a network of interconnected heating tunnels constructed beneath the building's floors (Figure 1). This design facilitates the transfer of heat through radiation, warming the floor surfaces and occupants by contact or thermal radiation.

The combustion process within the Tandoor generates hot air that travels through the tunnel or hypocaust, a network of channels constructed beneath the room’s floors [27]. This network of tunnels guides the warmed air throughout the designated rooms. Upon reaching the end of the circulation path, the heated air, containing smoke, is expelled through a designated outlet situated on the opposing wall [28]. The interior surfaces of these tunnels are lined with flat stones, functioning as radiant heat emitters that effectively warm the surrounding spaces. These flat stones possess a high thermal mass, a property that allows them to store significant amounts of heat. This stored thermal energy is then gradually released over a period of six to eight hours, contributing to the sustained warmth within the building.

The residual heat stored within the flat stones of the Tawa Khana system radiates upwards, warming the floor surfaces and subsequently the occupants of the room through thermal radiation. This passive heating system is typically operated two to three times a day, often coinciding with meal preparation times like breakfast and dinner. The height of the tunnels within the floor structure plays a crucial role in optimizing heat transfer. Studies have shown that the typical range for tunnel height in both Tawa Khana and Ondol systems falls between 0.15 and 0.4 meters. This specific height range facilitates the efficient circulation of the heated air and ensures the floor reaches a comfortable temperature for occupants. It is important to note that the optimal height may vary depending on factors such as the local climate and the specific heating system design.

Figure 2. Tawa Khana components: a) mud as a construction material, b) mud brick for tunnel construction, c) tandoor or fireplace, d) underfloor space and connector hole, e) tunnels f) network of tunnels, g) ventilation outlet.

A comprehensive survey of existing Tawa Khana systems in rural Afghanistan villages, as illustrated in Figure 2, sheds light on their construction practices. The underfloor spaces, or tunnels, are not built with a uniform height, but rather optimized for both the local climate and the specific function of the Tawa Khana within the dwelling. Notably, these tunnels are designed with a 4% incline to ensure efficient air circulation throughout the system. In some rare instances, a single, wider hypocaust tunnel can be used instead of multiple smaller tunnels, serving as the entire underfloor space. However, for larger rooms, multiple tunnels of specific widths are employed to ensure even heat distribution throughout the floor surface. Local flat stones are used to cover all the tunnels, facilitating effective heat transfer from the warm air to the floor above. These tunnels are strategically positioned beneath the room's floor and interconnected at both their entry and exit points within the designated space. On one end, the underfloor space connects to a fireplace or Tandoor through a clay pipe or dedicated tunnel for receiving heat. On the opposite side, an outlet on the wall allows for smoke to escape during operation but remains closed at other times to minimize heat loss. The design of the fireplace or Tandoor incorporates specific dimensions to enable simultaneous cooking and space heating. Constructed with special clay and precise measurements, the Tandoor typically features a bottom surface positioned 1.2 meters below the main room level. Furthermore, an exhaust system positioned 0.5 to 1.0 meters from the fireplace is incorporated into the Tandoor design to enhance its efficiency. A detailed breakdown of Tawa Khana dimensions, based on the aforementioned survey of existing structures, can be found in Table 1. The utilization of readily available materials and minimal financial investment associated with Tawa Khana construction makes it a suitable heating solution for various locations, particularly in regions with similar resource constraints.

Despite the current decline in urban application, the Tawa Khana concept presents a valuable opportunity for revitalization. Through targeted optimization of design and construction methods, these traditional heating systems can be further enhanced in terms of efficiency, paving the way for their reintroduction into contemporary building practices.

Table 1. Key dimensions of Tawa Khana elements, including heating sources (Tandoor) and underfloor spaces (Tunnels).

Tawa Khana features	Height (m)	Width (m)	Diameter (m)	Outlet diameter (m)
Tandoor or fireplace	1.2	-	1.2	0.1 – 0.15
Tunnel or hypocaust	0.4 – 0.5	0.4		0.15
Connector (Clay pipe)	-	-	0.1 – 0.2	

Therefore, this research examines the potential of Tawa Khana as a sustainable heating strategy, aiming to bridge the gap between its historical significance and its future applicability in modern building designs.

2.2. Simulation and Analysis

To effectively simulate and analyze the performance of Tawa Khana, a representative test room located within Kabul City, Afghanistan, was chosen as the primary model. Kabul, the nation's capital and most populous city, occupies the eastern region of the country at approximately 34°31′31″ North latitude and 69°10′42″ East longitude. The city encompasses 22 districts spread across a land area of 1,049 square kilometers and houses an estimated 396,095 dwelling units [14,29]. Kabul experiences a well-defined four-season climate featuring distinct dry periods. Spring encompasses the months of March, April, and May; summer spans from June to August; fall consists of September, October, and November; and winter unfolds from December to February. The overall climate of Kabul can be categorized as arid to semi-arid, with hot summers and cold winters. Winter temperatures can plummet to as low as -10°C, while summer temperatures can soar to 40°C [30,31]. The design of the test room was meticulously adjusted to conform to the established specifications for residential buildings in Kabul City, as detailed in Table 2. This ensures the model accurately reflects the typical dwelling unit where Tawa Khana would be implemented.

Table 2. Description of a test room for simulation input in the DesignBuilder program.

Test room	Description
Location	Kabul city, Afghanistan
Residential space	Living room
Ventilation type	Natural ventilation
HVAC	Cooling COP 3/ Heating COP 0.8
Heating set point	22 Co
Cooling set point	24 Co
Infiltration	Good
Room dimensions	6m x 6m = 36 m2
Room height	3 m
Window type	South-facing single window
Window to wall ratio	60 %
Glazing type	Trp Clr 3mm/13mm Arg
Wall	Outside Plaster + EPS +Brick-burned + Inside Plaster
Roof	Bitumen sheet + Cement mortar + EPS + Slap (Co-Reinforced) +Plaster
Floor	Carpet + Tiles + Mortar + Concrete + Gravel

DesignBuilder, a well-established Building Energy Modeling (BEM) tool, was chosen to simulate and analyze the performance of Tawa Khana. This software offers a comprehensive suite of functionalities for simulating various building elements during the design phase, promoting the development of energy-efficient building practices [32]. The decision to employ DesignBuilder in this study stemmed from its robust capabilities in conducting whole-building energy analyses and its ability to evaluate diverse aspects of a building's performance. Furthermore, DesignBuilder serves as a versatile platform, integrating functionalities for building performance simulation that encompass Computational Fluid Dynamics (CFD) analysis. Within DesignBuilder, CFD simulations are particularly useful for analyzing airflow patterns, temperature distribution, and contaminant transport within and surrounding buildings. This comprehensive approach to building performance simulation proved instrumental in analyzing the impact of various energy-saving strategies, particularly focusing on Tawa Khana. In this context, CFD analysis of Tawa Khana was employed to gain a deeper understanding of its airflow patterns, temperature distribution, and other critical performance metrics.

3. Results

The Tawa Khana system's performance was simulated under winter conditions at 9:00 am, representing the coldest time of day when the external temperature reaches -6°C. Previous research suggests that floor surface temperatures for radiant heating systems ideally fall within a range of 19°C to 29°C [25]. The simulation results demonstrate that the Tawa Khana system, operating at a high temperature, successfully elevated the floor surface temperature to 29°C. To ensure the accuracy of the findings, a comparative analysis was conducted. This analysis compared a baseline test room without Tawa Khana to a test room incorporating the Tawa Khana system. Detailed specifications of these test room configurations are provided in Table 3.

Table 3. Results obtained from simulating the test room with Tawa Khana and without Tawa Khana.

Test room description	Air Temperature		Surfaces Temperature						
	Outside	Inside (Room)	Floor Surface	Roof	North facing	North face Wall	East face wall	South face wall	West face wall
Baseline		12.5	13.7						
Tawa Khana	-6	*16.5*	29	13	8	13	13	13	13

The simulation results for the baseline test room, which does not incorporate a Tawa Khana system (as depicted in Figure 3), indicate a room temperature of 12.5°C. This temperature distribution is observed to be relatively uniform throughout space, with the exception of minor variations near the window. These variations likely stem from heat transfer processes occurring at the window due to its thermal properties. The simulation also revealed low airflow velocities within the baseline test room, ranging from 0 to 0.07 meters per second. This minimal air movement can be attributed to the absence of a heating system in the room.

The simulation results for the test room incorporating the Tawa Khana system (as depicted in Figure 4) reveal a significantly improved room temperature of 16.5°C. A notable difference in temperature is observed between the room air and the floor surface. The floor temperature reaches 29°C, effectively contributing to space heating through radiant heat transfer. Furthermore, the airflow patterns within the room exhibit greater variation compared to the baseline test room. Airflow velocities range from 0 to 0.22 meters per second, with noticeably higher velocities near the floor surfaces. This increased air circulation is a consequence of the Tawa Khana system's operation and contributes to improved heat distribution throughout the space.

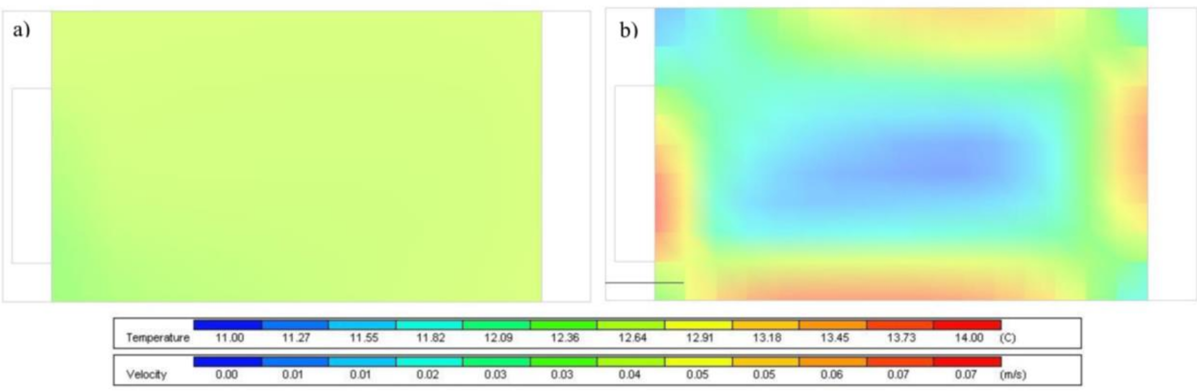

Figure 3. Temperature and airflow velocity of the test room surfaces in the absence of Tawa Khana (Baseline). a) Depiction of temperature distribution across the room section. b) Visualization of airflow velocity patterns within the room section.

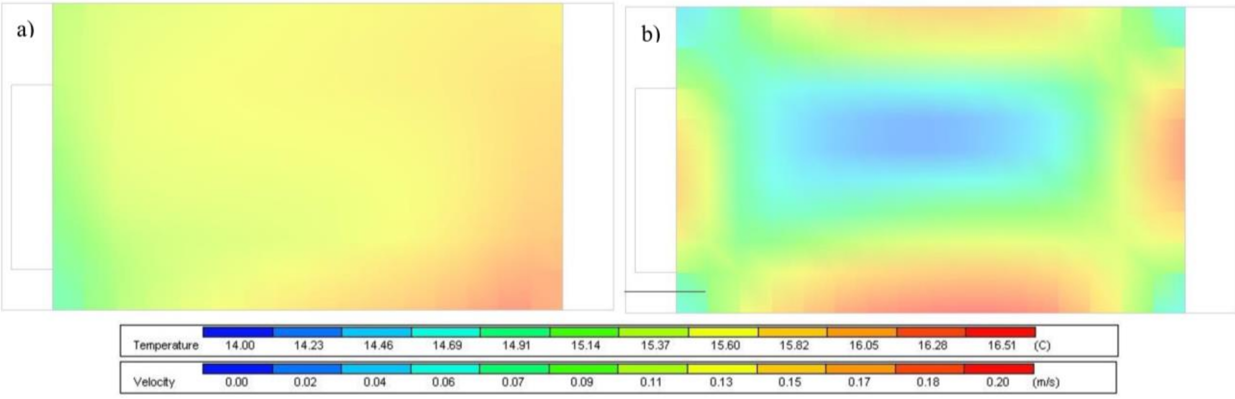

Figure 4. Temperature and airflow velocity of the test room surfaces with Tawa Khana. a) Depiction of temperature distribution across the room section. b) Visualization of airflow velocity patterns within the room section.

The simulation results demonstrate the effectiveness of Tawa Khana in achieving space heating. The floor surface temperature within the test room equipped with Tawa Khana reached 29°C, representing a significant increase of up to 16.5 degrees compared to the baseline model. This translates to a room temperature increase of approximately 4°C. This finding highlights the potential of Tawa Khana to utilize heat generated by household activities, such as cooking, for space heating purposes. By effectively capturing and distributing this waste heat, Tawa Khana offers an opportunity to conserve and utilize existing thermal energy for practical applications, potentially reducing the reliance on conventional heating systems.

4. Discussion

Vernacular architecture, encompassing the traditional building techniques and styles developed over generations by local communities, offers a rich repository of knowledge concerning energy-efficient design strategies. This body of knowledge emphasizes the importance of passive design principles, which involve the strategic design of buildings to leverage natural environmental resources for temperature regulation within the built environment. In warm climates, vernacular architecture often employs design features that promote shading and ventilation to achieve natural cooling effects. Conversely, buildings in cooler climates may incorporate design elements that facilitate solar heat gain and storage to maintain comfortable indoor temperatures. As a general principle, vernacular buildings frequently integrate features that promote the utilization of locally available and renewable energy sources, ultimately aiming to minimize reliance on non-renewable energy resources.

The Tawa Khana, a traditional Afghanistan’s heating system, exemplifies the ingenuity of vernacular architecture in achieving thermal comfort. This system utilizes a network of subterranean tunnels and a central Tandoor oven to efficiently distribute heat throughout a dwelling. Notably, the construction of Tawa Khana is characterized by its relative simplicity and affordability, primarily relying on locally available materials. However, despite these advantages, the application of Tawa Khana appears to be diminishing, primarily concentrated in rural areas. This study posits that through strategic design optimization and implementation, Tawa Khana can be revitalized as a viable and energy-efficient heating solution for contemporary buildings. The inherent merits of the Tawa Khana design offer several advantages. First, its dependence on local materials minimizes construction costs, making it a particularly attractive option for communities with limited resources. Second, the network of underground tunnels effectively captures and distributes heat generated by the Tandoor, promoting efficient fuel utilization. Furthermore, the inherent thermal mass of the earthen materials used in construction contributes to a long-lasting and stable heating effect. While the Tawa Khana system boasts these strengths, its potential for efficiency can be further amplified through targeted optimizations. Modern advancements in materials and technology can be strategically applied to refine the design of the underground tunnels. These refinements could focus on optimizing heat transfer efficiency while minimizing heat loss from the system. Additionally, the incorporation of readily available insulation materials presents another avenue for enhancing the overall thermal performance of the system. Furthermore, exploring alternative fuel sources for the Tandoor oven, such as biogas or solar power, holds promise for improving the system's sustainability and overall energy efficiency. Beyond its functional merits, the Tawa Khana represents a significant element of Afghanistan cultural heritage. By revitalizing and optimizing this traditional system, a twofold benefit can be achieved. This approach not only safeguards this cultural heritage but also offers a potential solution to the contemporary challenges faced by Kabul City, particularly regarding air pollution and energy consumption during winter months. A renewed focus on the Tawa Khana system, coupled with capacity-building initiatives for local craftspeople, can ensure the continued existence of this sustainable heating solution while fostering its integration into contemporary building practices.

5. Conclusions

Tawa Khana (Ondol) exemplifies a vernacular approach to heating that prioritizes environmental sustainability through its promotion of energy efficiency and sensitivity to site-specific factors. This radiant heating system utilizes heat generated from an underfloor furnace, fueled by various options such as wood, coal, or natural gas. A key advantage of Tawa Khana lies in its ability to efficiently capture and utilize waste heat produced during cooking activities. This reduces reliance on conventional heating systems, thereby promoting energy conservation within the dwelling. Furthermore, by directly heating the floor surface, Tawa Khana minimizes heat loss through convection and radiation mechanisms. This targeted heating approach contributes to superior energy efficiency compared to traditional heating systems that rely on air circulation for heat distribution.

The simulation results convincingly demonstrate the effectiveness of Tawa Khana in enhancing thermal comfort within space. By elevating the floor surface temperature from 13.7°C to 29°C, the system contributes to a notable increase in room temperature, rising from 12.5°C to 16.5°C. This translates to an approximate 4°C increase in room temperature, with the floor surface temperature playing a significant role in achieving occupant thermal comfort through radiant heat transfer. These findings highlight Tawa Khana's potential as a sustainable heating strategy. The system leverages locally generated heat from cooking activities to raise the room temperature effectively. The accompanying Figures 3 and 4 visually represent the distribution of thermal velocity and surface temperatures within the test room. The data suggests a clear trend of increasing temperature and air velocity emanating from the floor surface upwards through the Tawa Khana system, ultimately heating the room air. With the system typically activated two to three times a day, coinciding with meal preparation times, it is expected that continuous operation will lead to a further rise in room temperature, potentially reaching a comfortable set point of 22°C. This approach offers a promising avenue for achieving energy efficiency by addressing the building's heating demands while simultaneously ensuring the thermal comfort of its occupants.

This research underscores the potential of Tawa Khana, a traditional Afghanistan's heating system, as a viable and sustainable strategy for achieving energy-efficient buildings. The system's reliance on fundamental technologies and readily available resources aligns well with the principles of sustainable design. However, contemporary building practices often disregard this valuable approach, jeopardizing its continued existence. This study offers a comprehensive analysis of Tawa Khana, drawing upon evaluations of existing installations and building energy simulations. Table 1 details the design principles underlying this strategy and its potential to enhance building energy efficiency. By strategically optimizing these design principles and integrating advancements in modern technology, the performance of Tawa Khana can be significantly improved. This optimization process has the potential to position Tawa Khana as a compelling alternative to conventional heating systems employed in contemporary buildings.

Declaration

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article. The authors also declared that this article is original, was prepared in accordance with international publication and research ethics, and ethical committee permission or any special permission is not required.

Author Contributions

A.W.A. conceived the overall research design and methodology, conducted formal data analysis, and drafted the initial manuscript. M.I. provided supervision, guidance, and critical review of the manuscript. A.W.A. and F.I. contributed to data collection through on-site fieldwork and photography.

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