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Original Research Article

Design and Experimental Evaluation of a Multi- Layered Wall System for Heat Mitigation in Arid Environments

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Abstract

Food security in hyper-arid regions is constrained not only by water scarcity and soil degradation but by the thermodynamic instability of agricultural climates. In countries such as Qatar and across the Middle East and North Africa (MENA), extreme diurnal heat loads impose continuous cooling demand on controlled-environment agriculture, rendering food production energy-intensive and economically vulnerable. This study presents a novel multi-layered wall (MLW) designed to establish a controlled microclimate within interior agricultural environments under arid conditions. It is an arrangement of thermally useful materials: a high-thermal-mass clay composite for conductive attenuation; sequential semi-permeable membranes to interrupt and regulate convective exchange; a conditioned cavity that uses stack-driven airflow together with embedded cooling system; a concrete layer providing structural endurance and secondary buffering; and a recycled-plastic insulation layer to reduce residual flux. The assembly sequences moderate resistances and storage capacity to produce thermal lag, flux dispersion, and amplitude damping. Laboratory experiments under controlled radiative loading and sustained heat exposure verify the hypothesis: the MLW suppresses peak internal temperature excursions, flattens thermal gradients across interfaces, and preserves near-baseline interior conditions over prolonged forcing. Energy accounting for indoor farming loads suggests meaningful reductions in cooling demand when MLW-mediated temperature control replaces part of traditional mechanical conditioning. ***Index Terms***- *Multi-layered Wall* (MLW): Structural configuration designed for progressive reduction of heat transfer. *Thermal Insulation*: Layers and materials engineered to reduce conductive and convective heat flux. *Convective Ventilation*: Stack-driven airflow mechanisms that remove excess heat from the conditioning cavity. *Thermal Mass*: Use of clay-based composites and water loops to absorb and regulate transient heat loads. *Desert Agriculture*: Application of engineered microclimates to enable sustainable crop production under arid conditions. *Sustainable Development*: Meeting present developmental needs without compromising the ability of future generations to do the same.

Keywords: Desert agriculture, Extreme thermal environments, Multi-layered wall (MLW), Microclimate control.

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I. Introduction

Deserts face significant limitations for agriculture primarily due to extreme environmental conditions, leading to scarcity of vital resources and challenges for traditional farming practices. These limitations include severe aridity, high evaporation rates, poor soil fertility characterized by low organic matter and high salinity, restricted freshwater availability, elevated temperatures, and frequent sandstorms [1]. In the Middle East and North Africa (MENA) region, these challenges are particularly pronounced. The MENA region is one of the world's hotspots for water scarcity, exacerbated by climate change, rising temperatures, population growth, urbanization, over-extraction of groundwater, and water mismanagement [2]. Climate change projections indicate worsening conditions, including increasing aridity, reduced rainfall, and higher temperatures. For example, Morocco faces significant water stress with limited water resources and an annual per capita consumption of 700 m³ [3]. Soil degradation is a pervasive issue, with intensive land use, water scarcity, and climate change reducing soil quality across much of the MENA region, leading to desertification [4]. Specifically, in Qatar, a hot, arid country, agriculture has historically faced immense challenges due to the scarcity of water for irrigation. Qatar is almost entirely dependent on desalinated water, an energy-intensive process that can contribute to environmental concerns, including brine discharge [5]. A primary widespread problem stemming from agricultural limitations is increased vulnerability to global food supply chain crises and economic instability. Countries in the MENA region, characterized by arid conditions, are inherently reliant on food imports, making them susceptible to international market fluctuations, political instabilities in exporting nations, and disruptions in global supply chains [6].

Intensive land use, driven by the pressure to maximize limited arable land, coupled with water scarcity and global climate change, has led to widespread soil degradation across the MENA region. This degradation limits essential ecosystem services and poses a severe threat to remaining agricultural areas, increasing the risk of desertification [7]. Current solutions to these limitations in arid regions, including the MENA region and Qatar, involve adopting innovative agricultural technologies and water management strategies. One critical approach is the reuse of treated wastewater in agriculture, which helps to conserve freshwater resources for domestic needs [8]. Desalination, particularly solar-powered electro dialysis reversal (PV-EDR), is a promising technology for producing irrigation-grade water from brackish sources, thereby mitigating the problems associated with high-salinity irrigation water, such as decreased crop yield and soil degradation [9].

Reverse osmosis (RO) and Nano filtration (NF) desalination technologies are also being assessed for their performance in producing irrigation-grade water. [10]. Other advanced agricultural methods include controlled environment agriculture (CEA) such as hydroponics and vertical farming. These systems offer sustainable alternatives to traditional practices by maximizing productivity with limited resources and reducing carbon footprint [11].

Regarding water management, traditional irrigation knowledge is being integrated with modern sustainable practices to address water scarcity. Managed Aquifer Recharge (MAR) and rainwater harvesting are also being explored as methods for storing non- conventional water resources in arid regions [12]. Engineering soil substrates using block-structured designs (BSD) offer water-saving approaches for high- value crops by affecting evaporative losses and water distribution [13]. Xerophytic plants in arid environments have evolved natural adaptations, such as thick waxy cuticles, sunken stomata, and trichrome, to reduce water loss by manipulating the leaf boundary layer. These biological "multi-layered defenses" are inherent to the plants themselves, providing crucial protection against harsh conditions [14].

In hot arid regions like the MENA area, cooling is a major operational cost for CEA facilities. Multi- layered walls provide superior insulation and can integrate passive cooling strategies, significantly decreasing the energy required for cooling compared to less insulated structures [15]. These walls offer enhanced protection from external environmental stressors like high temperatures, sandstorms, and excessive solar radiation, which are prevalent in deserts and detrimental to crops in open fields [16].

The initial investment for constructing sophisticated CEA facilities with multi-layered wall systems can be substantial, limiting their widespread adoption, especially in resource-constrained areas. Empirical validation in hyper-arid environments for diverse agricultural applications remains somewhat limited, making it difficult to fully assess their long-term viability and return on investment in real-world scenarios. Maintenance of complex multi-layered structures can also be costly and labor-intensive. However, they provide superior insulation and can integrate passive cooling strategies, significantly decreasing the energy required for cooling compared to less insulated structures [17].

Although prior studies demonstrate the promise of thermal-mass greenhouses and shelterbelts for moderating temperatures and reducing evapotranspiration, there remains a shortage of integrated, field-tested, low-cost designs and empirical datasets tailored to MENA smallholder conditions. A research framework that evaluates microclimate regulation, soil moisture retention, irrigation demand reduction, and cost-effectiveness all within a single system would address this gap. Such work can generate site-specific empirical data, demonstrate measurable reductions in thermal stress and water loss, and provide a scalable, low-energy alternative or complement to high-technology agricultural systems.

II. MATERIALS AND METHODS

A. Materials Used

This section describes the materials employed in the construction of the proposed multi-layered wall system. The selection of materials was guided by their thermal properties, mechanical strength, durability under high-temperature exposure, and suitability for application in arid and semi-arid environments. Emphasis was placed on the use of passive materials capable of reducing heat transfer while maintaining structural integrity and environmental sustainability.

1.1 Clay-Based Composite Layer

Natural clay was utilized as the primary component of the outer thermal regulation layer due to its low thermal conductivity, high heat storage capacity, and long- standing use in vernacular architecture within hot climatic regions. The clay was processed to remove organic matter and coarse impurities prior to use. To enhance structural stability and resistance to cracking, ordinary Portland cement and fine sand were incorporated into the clay matrix. Two clay composite formulations were employed. The outer sub-layer was composed of clay, cement, and sand in a volumetric ratio of 2:1:1, selected to improve surface durability and resistance to environmental stress. The inner sub- layer consisted of a clay–cement mixture in a 5:1 ratio, optimized to increase thermal mass and reduce inward heat transmission. Together, these clay-based layers' function as a thermal buffer, moderating heat flux from the external environment.

1.2 Heat Moderator Membrane Materials

The heat moderator layer comprised three polymer- based mesh membranes fabricated from heat-resistant synthetic material. Each membrane was designed with an approximate surface distribution of 30 percent open area and 70 percent closed area. The material was selected to restrict direct airflow while minimizing convective heat transfer across the wall thickness. The membranes exhibit low thermal conductivity, dimensional stability at elevated temperatures, and resistance to mechanical deformation. Their layered configuration enhances thermal resistance by disrupting continuous heat flow paths without introducing significant structural load.

1.3 Conditioning Layer Materials

The conditioning layer incorporated materials intended to support passive thermal regulation through air and water interaction. Air conduits were fabricated from rigid polyvinyl chloride due to its low thermal conductivity, corrosion resistance, and mechanical durability. For thermal exchange, metallic piping manufactured from copper or aluminum was employed, selected for its high thermal conductivity and effectiveness in heat absorption and dissipation. These materials were chosen to enable efficient thermal interaction within the enclosed cavity while maintaining long-term operational stability under repeated thermal cycling.

1.4 Structural Concrete Layer

A structural concrete layer was included to provide mechanical strength and load-bearing capacity to the wall system. The concrete was prepared using stone aggregates, fine sand, and ordinary cement in a volumetric ratio of 4:2:1. Crushed stone aggregates with controlled particle size distribution were used to improve compressive strength and reduce internal void formation. This layer ensures structural stability of the multi-layered assembly without significantly compromising its overall thermal performance.

1.5 Recycled Plastic Insulation Materials

The innermost layer consisted of compressed recycled plastic panels produced from post-consumer plastic waste. The plastic was thermally processed and compacted to form dense panels with a fibrous internal structure and minimal air voids. This manufacturing approach resulted in improved compressive strength and reduced thermal conductivity compared to conventional plastic composites. In addition to its insulating function, the recycled plastic layer reduces the use of virgin polymer materials and decreases the cumulative material energy demand of the wall system.

▲ Figure 1.1 Prototype Built for Experimental Evaluation

B. System Design and Experimental Setup

A. Specimen geometry and layer configuration

The test specimen was a planar section of the multi- layered wall assembled to the dimensions required for laboratory evaluation. Layer thicknesses and compositions were as follows: outer clay composite, total thickness 12 cm (outer sub-layer 2.5 cm, inner sub-layer 9.5 cm) formed from clay–cement–sand (2:1:1) and clay–cement (5:1) mixes respectively; three polymeric heat-moderating membranes, each 5 cm thick with nominal 30 % open area and 70 % closed area, arranged with 3 cm inter-membrane air gaps; a conditioning cavity 10 cm deep containing an air distribution channel and an underground metallic water coil as water below surface level is substantially cooler which when moving through metal leads to cooling of surrounding air ; a structural concrete layer 4 cm thick (stone fragments : sand : cement, 4:2:1); and an innermost compressed recycled-plastic insulation panel 4 cm thick. The specimen was mounted on a rigid support frame.

B. Heat sources and boundary conditions

Two artificial radiative sources were available: a 70 W halogen lamp, employed as the primary controlled point heat source when noted, and a 120 W floodlight used for higher intensity or more spatially uniform irradiance exposures. For the principal test series reported in this study the 70 W halogen lamp was positioned within a concealed cardboard channel to concentrate radiative flux onto the external face of the specimen; the 120 W lamp was applied for selected high-intensity trials described in the test matrix. Ambient laboratory conditions were recorded and reported for each test. Tests were conducted indoors to eliminate direct solar irradiance and to control ambient convective conditions. The conditioning cavity was supplied with forced air via an electrically driven fan coupled to the wind turbine power system described in the Materials section; water circulated through the metallic coil in a closed underground loop to maintain lower inlet temperatures to the conditioning layer. Exhaust from the conditioning cavity was vented through the upper opening of the cavity to ambient laboratory air.

C. Test matrix and procedure

The test matrix comprised the exposure scenarios referenced in the Results section: (1) one-hour high- intensity exposure, (2) three-hour medium-intensity exposure, (3) ten-hour medium-intensity exposure, and (4) one-hour medium-intensity exposure with sequential measurements within the moderator gaps. For each test run the following procedural steps were executed: verify ambient conditions and sensor integrity, start continuous data logging, expose the external face to the prescribed heat source configuration, maintain the conditioning-layer air and water circulation at nominal operational settings, terminate the exposure at the scheduled interval, and continue logging until thermal transients diminished.

High Intensity light was artificially generated using 120-Watt flood light through a concealed tunnel of cardboard to focus on the external surface of the layer.

▲ Figure 2: 1 Hour high intensity heat exposure experiment to check the heat reduction capability of the wall made with selected materials in a specific ratio

▲ Figure 3: 3 Hour heat exposure experiment to monitor the heat conduction with continuous exposure to medium intensity heat

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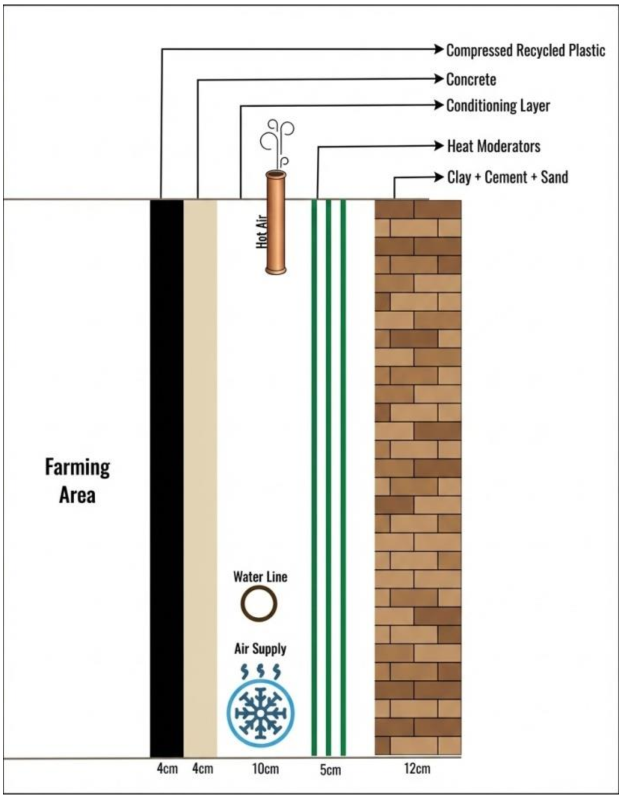
▲ Figure 4: 10 Hour heat exposure experiment Light artificially generated using 70-Watt Halogen Bulb through a concealed tunnel of cardboard to focus on the external surface of the layer (Without heat moderators and air vent)

▲ Figure 5: 1 Hour high intensity heat exposure experiment without heat moderators and air vent to observe the level of heat transmission



III.RESULTS

Thermal Response under Short-Duration High-Intensity Exposure

The thermal performance of the multilayer wall system was first evaluated under short-duration, high-intensity heat exposure using a 120 W floodlight. The experiment compared heat transmission behavior with and without the inclusion of heat-moderating membranes and ventilation.

Without heat moderators, the internal surface temperature increased from 27.9 °C to 33.7 °C within 1 h, corresponding to a net temperature rise of 5.8 °C. In contrast, when heat moderators and a 1 cm ventilation gap were incorporated, the internal temperature increased from 27.1 °C to only 29.7 °C, yielding a significantly lower rise of 2.6 °C. This represents a reduction of approximately 55 % in internal temperature rise relative to the non-moderated configuration.

Sequential temperature measurements across the wall thickness further demonstrate progressive thermal attenuation. After the cement layer, the temperature stabilized at 29.6 °C, followed by 28.2 °C after the first moderator and 27.4 °C after the second moderator, indicating effective suppression of conductive and convective heat transfer at each stage.

Temperature before heat exposure	29.6°C
After one-hour intense heat exposure	
External air temperature near the outer side	86.1°C
Outer side wall temperature	54.9°C
Inner side wall temperature	29.6°C

Table (1)

Under continuous medium-intensity exposure using a 70 W halogen source, the wall assembly exhibited strong thermal buffering behavior. While the external surface temperature increased substantially from 40.1 °C after 1 h to 51.3 °C after 3 h, the inner surface temperature remained comparatively stable, rising from 27 °C to only 28.5 °Cover the same duration.

This corresponds to a maximum internal temperature increase of 1.5 °C despite an external temperature escalation exceeding 10 °C. The large temperature gradient across the wall confirms the effectiveness of the multilayer configuration in attenuating sustained heat flux.

Temperature before heat exposure	27.5°C
After 3-hours medium intensity heat exposure	
External air temperature near the outer side	40.1°C
Outer side wall temperature	51.3°C
Inner side wall temperature	28°C

Table (2)

To assess thermal stability under prolonged exposure, the wall was subjected to 10 h of continuous medium- intensity heating without heat moderators or air vents. The mid-layer temperature increased marginally from 27.9 °C to 29.2 °C after 10 h, demonstrating high thermal inertia.

After termination of the heat source, the outer clay surface registered 58.4 °C, while the inner clay surface reached 31.5 °C. The concrete layer stabilized at 28.4 °C, and the innermost recycled plastic layer returned fully to baseline temperature (27.9 °C), indicating strong thermal decoupling and rapid recovery at the interior boundary.

Temperature before heat exposure	27.9°C
After 10-hours medium intensity heat exposure	
External air temperature near the outer side	40.1°C
Outer side wall temperature	58.4°C
Inner side wall temperature	27.9°C

Table (3)

Temperature before heat exposure	27.1°C
After 1-hour medium intensity heat exposure	
Temperature between wall and first moderator	29.1°C
Temperature between first and second moderator	28.2°C
Temperature between second and 3rd moderator	27.4°C

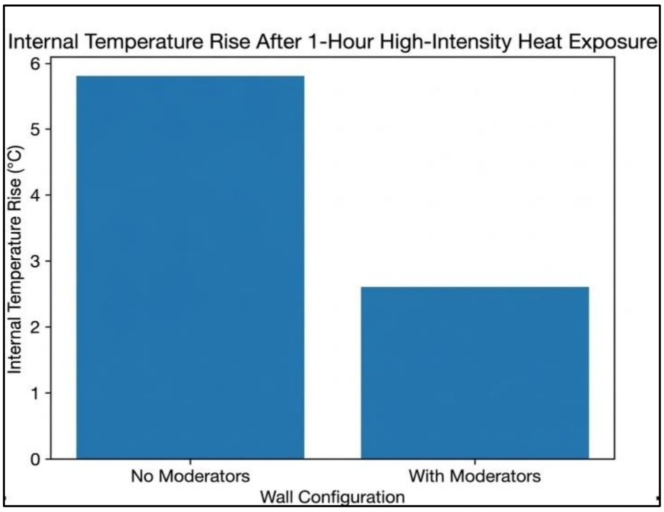
Table (4) **Table (4)**

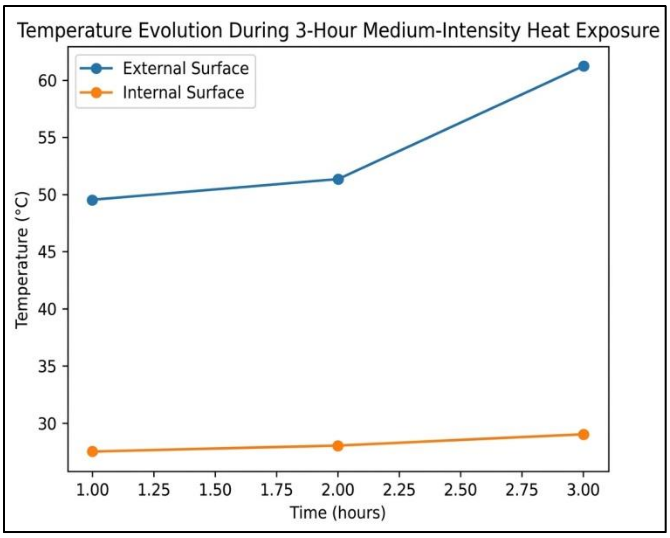
To quantify system effectiveness, temperature rise and attenuation efficiency were evaluated across experimental configurations. The results demonstrate that:

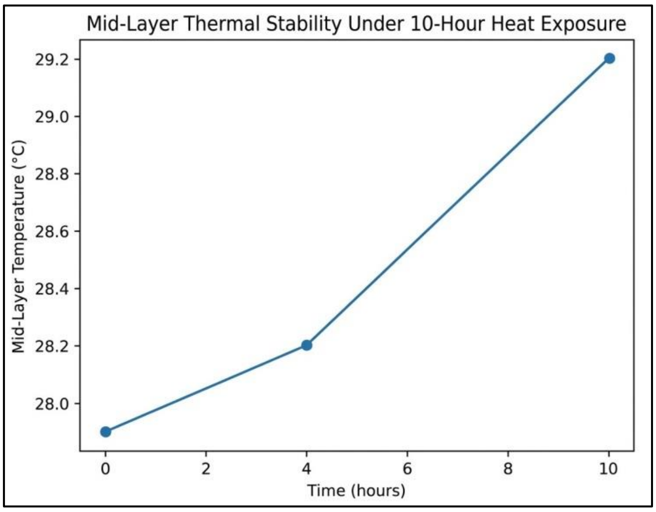
- Heat moderators reduce short-term internal temperature rise by more than half.
- Thermal mass dominates long-term stabilization.
- The innermost layer consistently maintains near-baseline temperature even under sustained heat loads.

4.5 Qualitative Interpretation

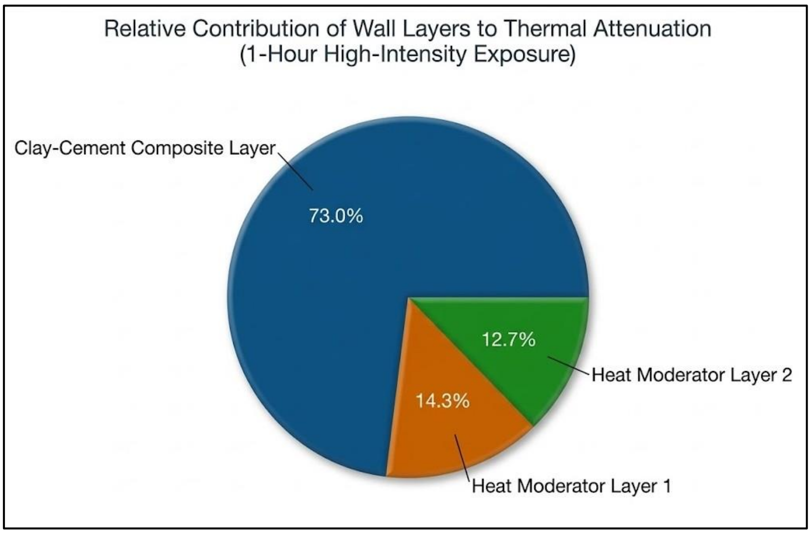
The clay-based outer layer provides substantial thermal inertia, delaying heat penetration and smoothing peak temperature fluctuations. Heat-moderating membranes reduce convective heat transfer by disrupting direct airflow paths, while the conditioning cavity enhances buoyancy-driven heat removal. The concrete layer provides structural support and secondary buffering, and the recycled plastic layer functions as a final thermal barrier, ensuring minimal inward heat flux.







The experimental results reposition the multi-layered wall not merely as a passive barrier, but as a thermally adaptive interface that restructures how desert heat interacts with agricultural space. Rather than minimizing transmission alone, the system reorganizes heat flow in time, redistributing external thermal energy across delayed intervals and reduced amplitudes. The earlier interface measurements demonstrate that no single layer governs performance; instead, the stratified coupling of thermal mass, convective interruption, and staged insulation generates a distributed buffering effect. This reveals an important conceptual shift: desert agricultural envelopes can function as dynamic thermal regulators, not static insulators.



A key implication of this behavior is operational resilience. Because the wall moderates heat flux before it reaches the crop zone, it reduces thermal shock events which are the rapid temperature spikes that most directly impair plant physiology. The observed time- lag opens the possibility of synchronizing wall behavior with diurnal agricultural cycles, aligning heat absorption and release with plant metabolic rhythms rather than ambient extremes. The observed performance aligns with established heat-transfer theory, where serial resistance and staged thermal mass yield exponential attenuation of heat flow, particularly under steady-state and quasi-steady thermal loading.

The attenuation does not collapse if one mechanism underperforms; conduction damping, convective disruption, and storage collectively sustain regulation. This distributed functionality suggests a pathway toward fail-safe passive agriculture. By maintaining internal conditions within a narrow operational band despite prolonged exposure, the system provides a structurally passive mechanism for microclimate stabilization that aligns with the constraints of arid regions, limited water, limited energy, and extreme heat.

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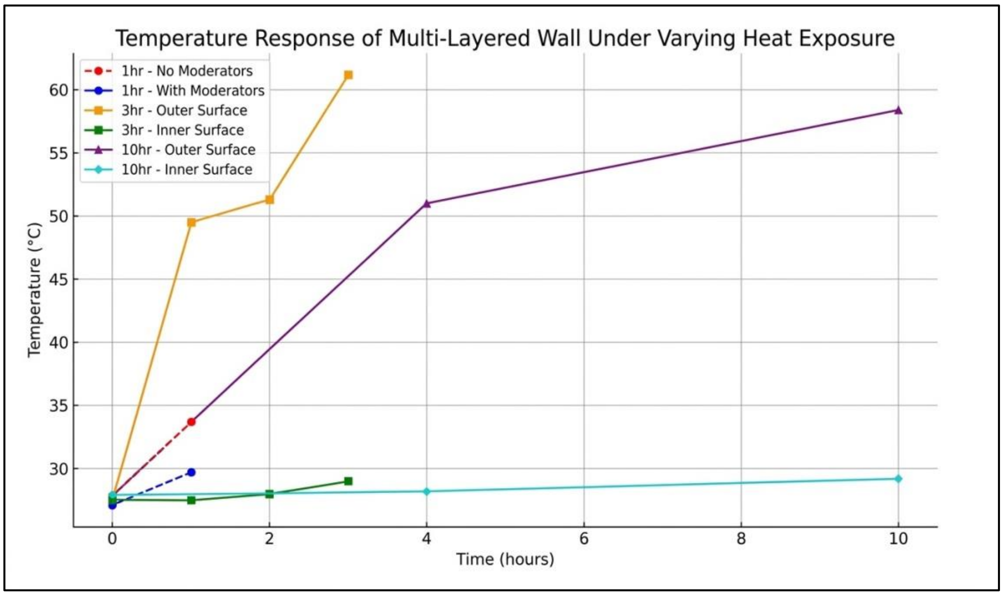


SURVEY CONDUCTED AND ANALYSIS

A public survey on desert vegetation and agriculture in Qatar was conducted to evaluate societal perceptions of sustainable farming practices, perceived constraints, and feasible strategies for crop cultivation under arid climatic conditions. The survey explored key themes including 365-day desert farming systems, bio-waste valorization, recycled plastic– based agricultural infrastructure, and in-house vegetable production as potential sustainability-driven approaches.

The findings indicate that a majority of respondents recognize the strategic importance of expanding agricultural activities as a means of generating employment opportunities and mitigating living costs within the State of Qatar. Poor soil quality and extreme summer temperatures were consistently identified as the primary limitations to agricultural productivity. Nevertheless, there was strong public endorsement of environmentally friendly and resource-efficient solutions to address these challenges.

Survey sample and response: A total of n = 44 individuals completed the survey between March– April 2024. Representation included residents from majorly Qatar, UAE, India, and sparsely from adjoining MENA countries.

Perceived importance of expanding agriculture: 87% of respondents agreed or strongly agreed that expanding domestic agriculture is strategically important for employment and cost mitigation.

Nearly unanimous agreement (42–44/44) on statements supporting:
natural seed/manure-based agriculture over genetically modified/chemical fertilizer approaches;

- repurposing bio-waste as manure;
- using recycled plastic in infrastructure;
- eco-friendly, cost-effective infrastructure and year- round (“365”) desert farming.

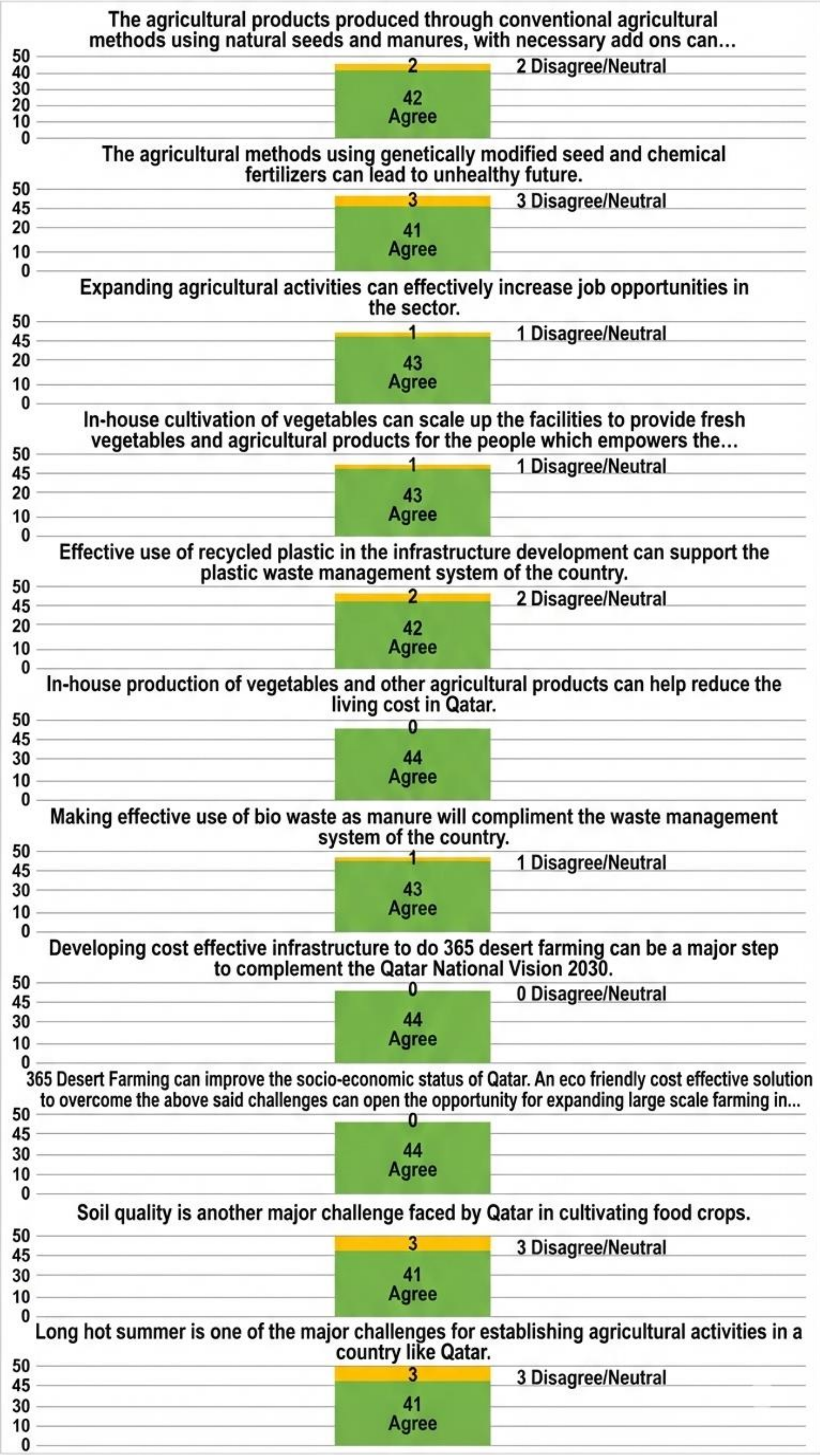
Statements identifying soil quality and long hot summers as major challenges received universal or near-universal agreement (soil quality: 44/44; long hot summer: 41/44). Respondents correctly identify the two most salient abiotic constraints for arid agriculture: thermal stress and poor edaphic conditions. This aligns directly with the technical objectives of the MLW (thermal regulation, substrate conditioning).

Paradoxically, respondents favor recycling plastic infrastructure and novel cost-effective engineering, but strongly prefer conventional seeds/manures over genetically modified (GM) approaches. The sample demonstrates instrumental technology acceptance: mechanical and material engineering solutions that are framed as circular and low-risk are acceptable; biological or genetic interventions perceived as “unnatural” or risky are resisted. This selective acceptance has implications for how MLW is framed and marketed.

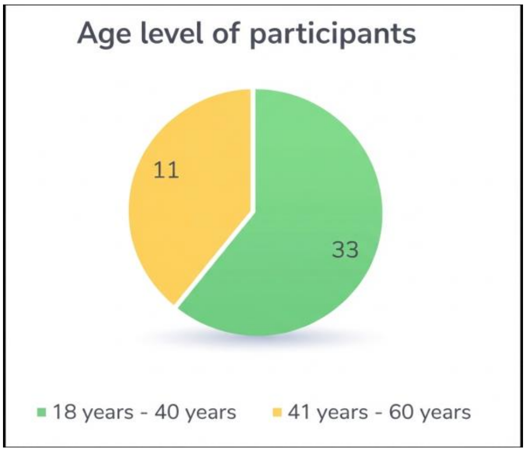
Respondents simultaneously express strong support for recycled plastic infrastructure (43/44) and universal concern regarding soil quality (44/44), indicating a preference for environmental-control and architectural interventions over direct soil engineering; this suggests that while structural solutions such as the MLW are socially acceptable, substrate remediation must be more explicitly integrated and communicated.

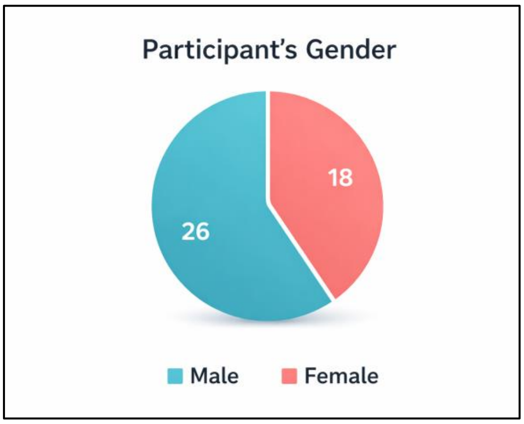
Age distribution (Figure 1) indicates that 33 participants were aged 18–40 years (approximately 61%), while 11 participants were aged 41–60 years (39%). This demonstrates a strong representation of younger adults, who are often more exposed to contemporary sustainability discourse and are likely to influence adoption of innovative agricultural technologies.

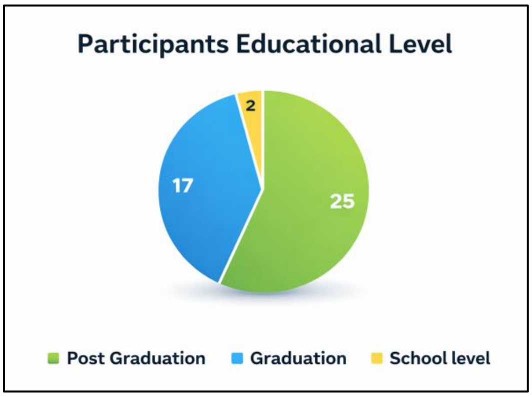
Gender distribution (Figure 2) shows a majority of male participants 26, (59%) and 18 female participants (41%). Educational level (Figure 3) illustrates that most respondents possessed graduate (25 participants, 46%) or postgraduate degrees (17 participants, 31%), with a small fraction (2 participants, 4%) reporting high school level education. This high educational attainment suggests that the sample has strong capacity to comprehend and evaluate technologically complex interventions.



The MLW's strengths: passive thermal regulation, use of recycled materials, and potential to reduce cooling energy or crop loss, all align well with public priorities.







IV. FURTHER DISCUSSION

The results demonstrate that the thermal performance of the multi-layered wall is governed primarily by dynamic heat-flow moderation rather than static insulation. Instead of eliminating heat transmission, the wall alters the temporal and spatial characteristics of heat propagation, converting a high-intensity external thermal load into a delayed and attenuated internal response. This distinction is significant in arid environments, where prolonged exposure to extreme temperatures makes time-dependent thermal behavior more relevant than steady-state resistance values.

Several higher-order interpretations emerge from the experimental trends.

- Thermal lag as the dominant mechanism: The minimal internal temperature rise observed even after extended exposure indicates that the outer clay-based layer and internal mass act as a thermal buffer, storing heat during peak exposure and delaying its inward progression. This confirms that thermal inertia, rather than thickness alone, is central to performance.
- Distributed resistance outperforming singular barriers: The stepwise temperature gradients across successive layers imply that heat

attenuation is achieved cumulatively. This supports the engineering principle that multiple moderate resistances arranged in series can outperform a single high-resistance layer by limiting direct conductive and convective coupling.

- Convective suppression rather than airflow elimination: The heat moderators do not function by sealing airflow completely but by disrupting coherent convective paths. This reduces the efficiency of heat transport while avoiding pressure buildup or complete stagnation, which can be counterproductive in layered assemblies.
- Controlled heat storage, not leakage: The gradual temperature rises in mid-layers, without a corresponding rise at the interior surface, indicates internal heat absorption rather than system inefficiency. This behavior reflects controlled heat storage within the wall thickness and should be interpreted as evidence of buffering rather than failure.

From a design perspective, the results imply that passive desert thermal control benefits more from mechanism sequencing than from material extermination. Increasing insulation alone would reduce heat flow but at the cost of material volume and structural load, whereas combining thermal mass, convective interruption, and a low-conductivity inner boundary achieves comparable or superior stabilization with greater efficiency. This layered strategy also enhances resilience, as partial failure or degradation of one component does not collapse overall performance.

At the same time, the experimental scope imposes clear boundaries on interpretation. The use of artificial heat sources simplifies analysis but does not fully replicate solar spectral distribution or diurnal cycling. In addition, limited repetition restricts statistical generalization. However, these constraints do not undermine the central physical insights, as the observed behaviors align with established heat-transfer theory and remain consistent across multiple exposure durations.

The stepwise temperature gradients measured across layers indicate cumulative attenuation: each material interface contributes impedance, partly reflecting and partly dissipating the heat flux. This series arrangement reduces coherent conductive coupling and provides redundancy: the failure or degradation of a single layer changes the transient response incrementally rather than catastrophically. Several building physics treatments show that properly sequenced moderate resistances plus internal mass often outperform an equivalently thick singular high-R layer when the design objective is reduction of peak internal temperature rather than minimal steady-state heat flow.

The layered approach increases resilience to local failure, aging or partial damage. Because heat is attenuated across several boundaries, partial loss of one layer reduces effectiveness gradually rather than abruptly; this is valuable for low-maintenance desert installations.

Overall, the discussion reframes the wall not as a passive shield but as a thermal regulator that actively reshapes heat flow using low-energy physical principles. This perspective is particularly relevant for arid agricultural systems, where sustainability constraints demand solutions that moderate extremes rather than attempt to eliminate them entirely. The findings therefore position multi-layered, passively moderated wall assemblies as a structurally integrated approach to microclimate stabilization, bridging the gap between conventional insulation and energy- intensive active cooling.

A typical indoor farming setup would rely on a 1.5-ton air conditioning unit (approximately 5.2 kW) operating for 10 hours daily to maintain an internal temperature of 28°C during peak external temperatures reaching 50–55°C. This results in an estimated daily energy consumption of:
5.2 kW × 10 hours = 52 kWh/day

Experimental data from high-intensity heat exposure revealed that, without heat moderation, the internal temperature of the interior rose to approximately 33.7°C. In contrast, the multi-layered wall system limited the internal temperature to ~30°C, maintaining conditions much closer to the optimal cultivation range without the use of mechanical cooling. Since every 1°C increase in the temperature differential typically results in approximately a 6% increase in air conditioning energy demand, the observed 3.5°C reduction in internal heat gain corresponds to an estimated 21% reduction in cooling energy consumption.

Thus, the multi-layered wall system potentially saves:
0.21 × 52 kWh/day = ~10.92 kWh/day Over the course of one year, this equates to:
10.92 kWh/day × 365 days = ~3,986 kWh/year

In environmental terms, assuming a conservative emission factor of 0.45 kg CO_2 per kWh (typical for partially fossil-fuel-based grids), this translates to: 3,986 kWh × 0.45 kg CO_2/kWh = **~1,793 kg (1.8 metric tons) CO_2 / year avoided**.

V. LIMITATIONS

Heat Source Accuracy- The use of halogen and floodlights as a heat source does not perfectly mimic the full spectrum and intensity of natural sunlight. As a result, the thermal stress recorded in this experiment may slightly differ from actual conditions in a desert environment.

Testing Duration- The experiment was limited to short-term exposures (1-hour and 10-hour intervals). Because real desert conditions involve continuous heat over much longer periods, these results may not fully represent how multilayer walls perform over weeks or months of heat saturation.

Prototype Scale- This study used small-scale prototypes rather than full-sized walls. Moving to full-scale construction could introduce new variables, such as thermal bridges (areas where heat leaks through more easily) or different structural behaviors under heat.

Environmental Variables- Testing was conducted in a controlled indoor environment using cardboard tunnels. This approach does not account for unpredictable outdoor factors like humidity fluctuations, wind cooling effects, or natural shifts in ambient temperature.

VI. ACKNOWLEDGEMENTS

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