Current Research in Agricultural Sciences
2025 Vol. 12, No. 2, pp. 202-215
ISSN(e): 2312-6418
ISSN(p): 2313-3716
DOI: 10.18488/cras.v12i2.4600

Integrated environmental control strategy for vertical wheat farming in arid climates: Linking crop physiology and energy systems for sustainable cereal production

Nour Elhouda Hallas[1+]
Alejandro Moreno-Rangel[2]

[1,2]*Department of Architecture, University of Strathclyde, Glasgow, United Kingdom.*
[1]*Email: nour.hallas.2021@uni.strath.ac.uk*
[2]*Email: alejandro.moreno-rangel@strath.ac.uk*

(+ Corresponding author)

Article History
Received: 3 November 2025
Revised: 5 December 2025
Accepted: 15 December 2025
Published: 19 December 2025

Keywords
Arid climates
CO_2 enrichment
Controlled-environment agriculture
Energy efficiency
Food security
Hydroponics
North Africa
Vertical farming
Wheat.

ABSTRACT

This study aims to develop an integrated environmental-control framework for vertical wheat farming in arid climates, addressing the challenges of resource scarcity, climate stress, and wheat import dependency in regions such as North Africa. The purpose is to align the crop's physiological requirements with energy, environmental, and economic constraints in order to evaluate its feasibility within controlled-environment agriculture. The design and methodology draw on recent advances in lighting optimization, CO_2 enrichment, indoor-climate regulation, and hydroponic water recycling, combined with techno-economic analysis of energy demand and system-level integration. Insights from plant physiology and environmental engineering are synthesized into coordinated control strategies that balance grain-yield optimization with reductions in energy and water consumption. The findings confirm that electricity use, particularly for lighting and cooling, is the principal feasibility barrier for cereal-scale vertical farms, typically accounting for 60–70% of operating costs. However, the integration of adaptive lighting schedules, CO_2 recycling, hydroponic recirculation, waste-heat recovery, and on-site solar generation can reduce energy-use intensity to below 250 kWh t^{-1} of biomass while achieving ≥90% water savings and improved CO_2-use efficiency. The practical implications include a system-level strategy that links environmental parameters to resource-use efficiency, operating costs, and yield quality, providing a replicable blueprint for future pilot facilities in hot-arid economies. Rather than replacing field agriculture, the framework positions vertical wheat farming as a strategic resilience tool to strengthen food-security planning under climate and market volatility.

Contribution/Originality: This study contributes to the literature by proposing a novel integrated environmental-control framework that combines crop-physiological requirements with energy-system optimization for wheat cultivation in arid climates. It is among the first to translate engineering and agronomic parameters into a unified techno-economic design strategy for vertical cereal production.

1. INTRODUCTION

Food security is an escalating concern in arid and semi-arid regions, where climate change, population pressures, and resource scarcity converge to undermine agricultural sustainability [1-3]. Rising temperatures, more frequent droughts, and increasingly erratic rainfall patterns reduce crop yields and intensify volatility in food supply. For staple crops such as wheat, these challenges are particularly acute: every 1 °C increase in global mean temperature may reduce yields by 6–20 %, with the most severe impacts occurring in already water-stressed regions [4-6]. These dynamics pose critical risks for the Middle East and North Africa (MENA), where climatic exposure intersects with structural economic vulnerability.

Wheat is the dietary cornerstone across North Africa, supplying most caloric and protein intake. In Algeria, for instance, annual per-capita wheat consumption averages 180–220 kg, nearly three times the global mean [7, 8]. National demand exceeds 10 million tonnes per year, while domestic production seldom surpasses 2–3 million tonnes, resulting in recurring imports of 7–9 million tonnes. Similar dependency levels in Egypt, Tunisia, and Morocco leave regional food systems highly exposed to fluctuations in global markets [3, 9]. The Russia–Ukraine conflict in 2022 made this vulnerability particularly evident: price spikes and export restrictions disrupted supply chains, revealing the fragility of MENA's reliance on imports for more than 60% of consumption. If current trends persist, import dependency may exceed 50% by 2050 [9, 10].

Controlled-environment agriculture (CEA) and vertical farming have emerged as complementary strategies to conventional field agriculture by decoupling production from weather variability and seasonal constraints [3, 11]. In vertical farms, crops are cultivated in stacked layers under controlled conditions of light, temperature, humidity, and carbon dioxide (CO_2) concentration, enabling year-round production [4, 6]. These systems are already commercially successful for short-cycle, high-value crops such as leafy greens and herbs [11, 12], achieving up to 95% reductions in water use and maximising land-use efficiency in urban settings [13-15].

Extending this model to wheat, however, introduces substantial challenges. Wheat's long growth cycle, tall morphology, and high demand for light and CO_2 result in energy requirements three to five times greater than those of leafy greens. Extended photoperiods (≈ 14–16 h) and higher light intensities (≈ 300–600 $\mu mol\ m^{-2}\ s^{-1}$) significantly increase electricity use and operational costs [4, 5, 16]. Although pilot studies demonstrate technically feasible yields exceeding 100 $t\ ha^{-1}\ yr^{-1}$, more than 25 times typical field yields, production costs remain prohibitive at > USD 1,000 per tonne, compared with import prices of USD 250–300 [3, 7, 8]. Consequently, the central research question shifts from whether wheat can be grown indoors to whether it can be produced efficiently and sustainably within the economic and resource constraints of arid-zone economies.

This study develops an integrated environmental-control strategy for vertical wheat farming in arid climates. Drawing on advances in lighting, CO_2 enrichment, and indoor climate management, it seeks to establish quantitative links between environmental parameters and techno-economic performance. The contribution lies in integrating physiological crop requirements with energy-system optimisation to support sustainable wheat production in resource-limited regions.

2. WHEAT GROWTH REQUIREMENTS

Wheat is a globally adaptable cereal, yet its productivity is highly sensitive to environmental conditions. In vertical farming and controlled-environment agriculture (CEA), these conditions can be precisely regulated, enabling stable yields in arid regions where heat stress, water scarcity, and erratic climate patterns undermine field-based production [17-20]. This section reviews the principal physiological requirements of wheat when cultivated under controlled environments.

2.1. Temperature

Temperature strongly influences wheat phenology, growth rate, and stress responses. Optimal development typically occurs between 15–25°C, with stage-specific thresholds of 15–20°C during tillering and 20–23°C at anthesis considered critical for *maintaining* yield stability [17-21]. Temperatures above 30°C during flowering can induce spikelet sterility, while prolonged exposure beyond 35°C may result in substantial yield losses [4, 22].

2.2. Light and Photoperiod

Wheat is a facultative long-day crop. Photoperiods of approximately 14–16 h accelerate development without compromising grain quality, whereas extreme photoperiods exceeding 20 h are used primarily for speed-breeding and substantially increase energy demand [23-25]. The target daily light integral (DLI) ranges from 20–30 mol m^{-2} day^{-1}, generally achieved through photosynthetic photon flux density (PPFD) of 300–600 µmol m^{-2} s^{-1} delivered across the canopy. Light spectra dominated by red (≈80–90%) and supplemented with blue (≈10–20%) wavelengths, with limited far-red, optimize crop morphology and photosynthetic efficiency [4, 6, 11].

2.3. CO_2 Concentration

As a C_3 species, wheat exhibits strong photosynthetic and yield enhancements under elevated CO_2. Optimal enrichment lies between 700 and 1,000 ppm during the light period, beyond which diminishing returns occur. Concentrations above 1,200 ppm may reduce grain-protein content unless nitrogen supply is carefully adjusted [26, 27].

2.4. Relative Humidity and Water Use

Relative humidity (RH) plays a central role in regulating transpiration, disease development, and final grain quality. Optimal RH ranges are approximately 70% during vegetative growth, 60% at anthesis, and 50% during ripening [16, 23, 26]. Levels above 80% favor fungal proliferation, whereas RH below 40% induces water-stress responses. Hydroponic systems with recirculation and condensate recovery can reduce total water consumption by 90–95% compared with conventional field production [3, 6, 28].

2.5. Airflow

Airflow management is essential in vertical wheat systems. Gentle air circulation of 0.2–0.5 m s^{-1} around the canopy helps prevent humidity pockets, facilitates pollination, and reduces fungal risk, while avoiding excessive stem movement or evaporation losses [11, 27].

Table 1 summarizes the optimal environmental parameters for wheat cultivated under controlled-environment agriculture. These ranges define the physiological envelope required for successful indoor wheat production; achieving them consistently in arid climates necessitates advanced environmental-control strategies to minimize both energy and water costs.

Table 1. Physiological requirements of wheat in controlled-environment agriculture (CEA).

Parameter	Optimal range in CEA	Notes
Temperature	Day ≈ 20–23 °C; Night ≈ 15–18 °C	Overall optimum ≈ 17–23 °C; slightly cooler (≈16 °C) at spikelet initiation; avoid > 30 °C (sterility risk).
Photoperiod	14–16 h light per 24 h (long-day)	Accelerates development; a dark period (4–8 h) supports respiration; > 20 h used in speed-breeding [23].
Light intensity	300–600 µmol m^{-2} s^{-1} PPFD	Achieve DLI ≈ 20–30 mol m^{-2} day^{-1}; red (≈ 80 %) + blue (≈ 20 %) spectra optimal.
CO_2 concentration	700–1 000 ppm (daytime)	Enrichment boosts yield ≈ 30 %; returns diminish > 1,000 ppm; maintain adequate N supply [26].
Relative humidity	60–70 % (vegetative); 50–60 % (reproductive)	Moderate RH limits stress and pathogens; avoid > 80 % (disease) or < 40 % (stress).
Water supply	Hydroponic, full evapotranspiration replacement	Recirculation + condensate recovery ≈ 90 % water saving vs. field [28].
Airflow	0.2–0.5 m s^{-1} around the canopy	Prevents humidity pockets and aids pollination; excessive speed damages stems.

Source: Bao et al. [17], Chavan et al. [18], Wheeler et al. [21], Sheehan and Bentley [22], Harris et al. [23], Wang and Liu [26], and [28].

3. CONTROL STRATEGY FOR WHEAT IN ARID CLIMATES

3.1. Integrated Control Objectives

Designing a control strategy for wheat cultivation in vertical farms under arid conditions requires a holistic perspective that integrates physiological optimisation, resource efficiency, economic feasibility, and system resilience. In traditional agricultural systems, these domains are often managed independently; for instance, irrigation decisions may be made without considering fertiliser scheduling, but in controlled-environment agriculture (CEA), the tight coupling of energy, water, and CO_2 cycles means that control actions in one domain directly influence all others. For wheat, which is highly sensitive to thermal stress and photoperiod and exhibits high energy and water demands, the challenge is to harmonise production within environmental and economic constraints rather than maximise yield at any cost.

This integrated perspective is especially critical in arid regions, which face three overlapping stressors. (1) resource scarcity, with agriculture accounting for more than 80% of national freshwater withdrawals; (2) economic pressure, as wheat imports represent billions of USD annually and impose fiscal vulnerability; and (3) climate risk, with projected increases in mean temperature, drought frequency, and precipitation variability [1-3].

A vertical-farming control strategy for wheat must therefore achieve four interlinked objectives derived from recent research on CEA and arid-climate optimization [4, 6, 11, 16]. These objectives directly reflect the constraints that shape feasibility in arid and semi-arid regions.

1. Crop-performance optimization involves maintaining temperature, humidity, CO_2 concentration, and light within physiologically optimal ranges to maximize grain yield and quality per cycle. Unlike leafy greens, wheat has narrow stress thresholds, particularly during anthesis and grain filling, making precision control essential [4, 24].
2. Resource efficiency: minimizing water and energy consumption through recycling, recovery, and adaptive scheduling. In arid economies, resource intensity directly influences competitiveness, as water tariffs, desalination *energy*, and electricity subsidies significantly affect production costs [3, 6].
3. Economic sustainability involves aligning production costs with import benchmarks. In contexts where imported wheat is priced at 250–300 USD t^{-1}, domestic controlled-environment production must progressively approach this range to achieve economic credibility [7, 8].
4. Scalability and resilience enable operability under variable electricity supply, evolving policy conditions, and climatic extremes through modularity, redundancy, and coordinated energy-management systems [10, 12].

The novelty of this strategy lies in its system-level integration: rather than managing environmental-control parameters independently, it dynamically balances them to optimize yield trajectories under energy and cost constraints. This signifies a shift from purely technological optimization to techno-economic optimization, aligning with policy goals such as SDG 2 (Zero Hunger), SDG 7 (Affordable and Clean Energy), and SDG 13 (Climate Action).

Figure 1 summarizes the proposed analytical control framework linking arid-climate context to environmental-control levers through a systems-integration layer and key performance benchmarks. Tables 2 and 3 translate these levers into operational targets and performance indicators.

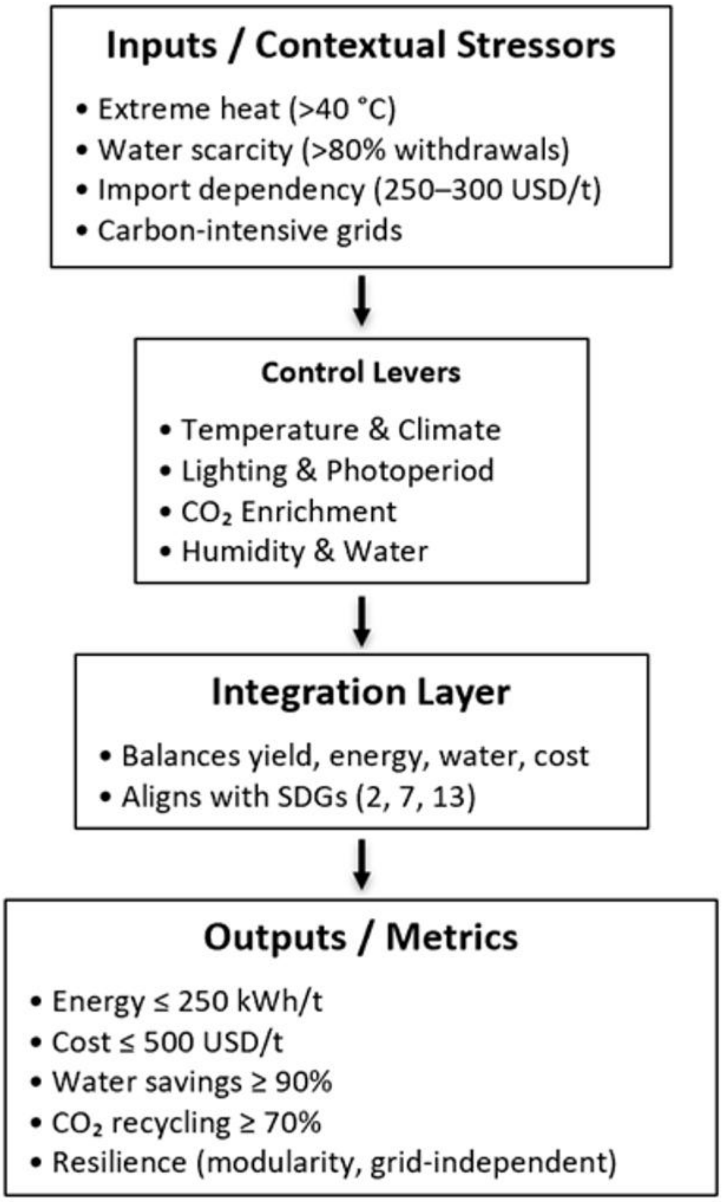

Figure 1. Analytical strategy linking arid-climate context to environmental control levers, a system-integration layer, and performance benchmarks for indoor wheat in vertical farms.

Table 2. Integrated control strategy for wheat in arid climates.

Objective	What it ensures	Primary control levers	Trade-offs to manage
Crop performance optimization	Wheat maintained within physiological optima	Temperature and RH set-points; PPFD and photoperiod; CO_2 scheduling	Protein dilution at high CO_2; heat stress at anthesis
Resource efficiency	Reduced energy and water intensity	Adaptive set-points; hybrid LED + daylight integration; condensate and waste-heat recovery	Dimming versus biomass output; dehumidification energy penalty
Economic sustainability	Pathway to cost parity	PV + storage integration; demand shifting; scale economies	CAPEX burden; tariff exposure
Scalability and resilience	Operability under environmental or grid shocks	Modular rooms; grid/storage hybrids; EMS coordination	System complexity; O&M skill requirements

Source: Kalantari et al. [3], Asseng et al. [4], Shen et al. [6], Al-Kodmany [10], Kozai [11], and Ali [16].

3.2. Control Strategies by Parameter

Building on the physiological requirements described in Section 2, the following strategies translate these needs into operational solutions for arid-climate vertical-farming systems.

3.2.1. Temperature and Climate Control

Ambient summer temperatures above 40°C make thermal regulation a major challenge. The proposed strategy combines passive and active measures, including high-performance insulation, reflective envelopes, staged zoning, and night-time evaporative cooling, supported by high-efficiency variable-speed heat pumps. Adaptive set-point scheduling (cooler during vegetative phases, warmer during grain filling) can reduce cumulative cooling energy by up to 20% without yield penalties [21-23].

3.2.2. Lighting and Photoperiod: Control Rules and Trade-offs

Achieving the target daily light integral (DLI) for wheat with minimal energy per mole of photons, while preserving normal developmental timing and morphology, is essential for operational efficiency [4, 6, 11].

Efficient light management begins with stage-adaptive dimming, gradually increasing photosynthetic photon flux density (PPFD) from early tillering to pre-anthesis to avoid over-illumination of young canopies. This approach can reduce lighting energy by approximately 10–20% without compromising growth [21, 24].

Photoperiod control acts as an additional optimization lever: maintaining 14–16-hour regimes but shifting the timing by one to two hours enables operators to move lighting loads away from high-tariff periods under Time-of-Use (ToU) pricing, reducing operational expenditure [3, 12]. Where architectural design allows, hybrid daylighting, via translucent photovoltaic panels or clerestory glazing, can partially substitute grid electricity, typically reducing electrical demand by 10–20%.

Spectral composition is equally critical. A predominantly red spectrum (≈80–90%) maximizes photosynthetic efficiency, while 10–20% blue light maintains leaf thickness and controls elongation. Short pulses of far-red during developmental transitions (e.g., heading) can accelerate flowering without continuous exposure, which would otherwise increase internode length and energy demand [21, 24].

Because lighting and HVAC loads are tightly coupled, quantum sensors regulate DLI-based dimming while the environmental management system (EMS) coordinates light intensity with cooling capacity to avoid coincident electrical peaks. Waste heat from LED drivers can be recovered through low-temperature liquid-cooling loops or heat exchangers, feeding residual thermal energy into HVAC circuits to improve system-level efficiency [5, 6]. Excessive lighting increases canopy temperature and vapour-pressure deficit (VPD), raising transpiration and dehumidification loads. These effects are mitigated by setting PPFD upper thresholds linked to acceptable VPD ranges and using leaf-temperature feedback sensors to fine-tune intensity [4, 11]. Through this coordinated approach, lighting becomes both a driver of photosynthesis and a central component of an integrated energy-management strategy for vertical wheat production in arid climates.

3.2.3. CO_2 Enrichment

Control objective: Maximize photosynthetic efficiency only when adequate light is available, while preventing waste and maintaining grain-protein quality through coordinated nitrogen management [26, 27, 29].

As outlined in Section 2, optimal CO_2 levels range from 700 to 1,000 ppm. Maintaining these concentrations efficiently requires synchronizing injection with the photoperiod: enrichment operates only during light hours, with ambient levels maintained at night to avoid unnecessary consumption. Demand-driven control using canopy-level infrared-gas analysis (IRGA) or non-dispersive infrared (NDIR) sensors, configured with dead bands to prevent frequent cycling, ensures stability [6, 27]. In multi-tier configurations, zonal delivery through per-tier manifolds limits stratification and maintains uniformity, verified periodically through spatial concentration mapping.

From a supply perspective, industrial symbiosis offers cost-effective, low-carbon CO_2. Capturing food-grade CO_2 from nearby fertiliser or cement plants reduces both cost per kilogram and scope-2 emissions [3, 27]. Leak-tight distribution lines and accurate metering ensure efficient delivery and reliable life-cycle accounting.

Sustaining nutrient quality under elevated CO_2 requires integrated nitrogen management. To mitigate protein dilution effects, enrichment should be paired with stage-specific nitrogen supplementation, typically via timed fertigation pulses supported by monitoring tools such as SPAD or NDVI indices during grain filling [24, 26].

Finally, CO_2 control must be coordinated with HVAC operation. Increased CO_2 uptake and respiration <<alter>> latent and sensible loads; therefore, enrichment should avoid periods when dehumidification capacity is constrained. This coordination prevents excessive energy use and maintains stable energy intensity per tonne of biomass [6, 11].

3.2.4. Humidity and Water Use

Hydroponic recirculation and condensate recovery can reduce water demand by 90–95 % [3, 28]. In arid climates, desiccant dehumidifiers with waste-heat recovery exploit dry ambient air while recycling captured condensate. Stage-specific relative humidity (RH) control, approximately 70% during vegetative growth, 60% during flowering, and 50% during ripening, balances water efficiency and disease suppression [6, 24].

3.3. Energy, Cost, and Sustainability Metrics

Energy consumption remains the dominant constraint on both cost and sustainability in cereal-scale vertical farms. Electricity typically accounts for 60–70% of total operating expenditure, primarily driven by lighting and climate-control loads [6, 11, 12]. This emphasizes that energy use, not crop physiology, defines the primary feasibility boundary for vertical wheat production in arid regions.

Within total energy demand, LED lighting accounts for approximately 40–60%, while HVAC systems contribute a further 30–40% through cooling, dehumidification, and air circulation. Pumps, fans, sensors, and automation systems form a smaller but still significant share. Because many arid-region grids are carbon-intensive with relatively high tariffs, effective energy management becomes the critical determinant of techno-economic viability [3, 30].

To mitigate these constraints, the proposed integrated strategy employs a hybrid energy system that combines on-site renewable generation with heat recovery and storage. Photovoltaic (PV) generation supplies daytime renewable electricity and reduces dependence on the grid, while battery storage smooths fluctuations and supports nighttime operation. Reversible air-to-water heat pumps recover waste heat from LED drivers and condenser units, supplying low-temperature heating during germination or cooler seasons. Parallel heat-recovery loops capture residual thermal energy from lighting and dehumidification subsystems, recirculating it through the hydronic network to enhance overall system efficiency [6, 10, 31].

Based on these integrations, the system targets an energy-use efficiency (EUE) of ≤ 250 kWh t^{-1} of wheat biomass, compared with current pilot reports of 300–400 kWh t^{-1} [16, 31]. Achieving this benchmark requires coordinated control across lighting, HVAC, and storage subsystems, supported by adaptive scheduling and renewable-generation forecasting [6, 11].

3.3.1. Energy Demand and Efficiency

3.3.2. Economic Metrics

Economic viability depends on narrowing the gap between indoor production costs and global import prices. Algeria, for example, imports wheat at approximately 250–300 USD t^{-1} [7, 8]. Current indoor production costs exceed 1,000 USD t^{-1}, but integrated renewable-energy systems, resource recycling, and scale economies have the potential to reduce costs significantly over time [4, 12].

Proposed economic targets:

- Production cost ≤ 500 USD t^{-1} by 2030.
- Energy share of operating costs ≤ 40 %.
- Payback period < 10 years per facility.

Meeting these targets will require policy support, including renewable-energy incentives, preferential electricity tariffs, and public–private partnerships to reduce CAPEX burdens.

3.3.3. Sustainability and Resilience

Beyond economic considerations, sustainability metrics must reflect water efficiency, carbon footprint, and land-use intensity. Closed-loop hydroponic systems should achieve ≥ 90% water savings and ≥ 70% CO_2-recycling efficiency relative to open-field production [16, 28].

Resilience indicators, such as reduced dependence on global wheat markets, the ability to operate under variable grid conditions, and modular scalability, are particularly important for strengthening food security in North Africa [2, 9].

3.3.4. Strategy Summary

Together, the energy, cost, and sustainability dimensions define the feasibility envelope for vertical wheat farming in arid and semi-arid climates. Unlike temperate regions, arid economies face extreme cooling loads, chronic water scarcity, and variable grid stability, all of which shape the operational priorities of the proposed strategy.

Energy-efficiency targets must respond to high ambient temperatures, requiring advanced insulation, adaptive HVAC control, and robust heat-recovery systems. Water benchmarks emphasize hydroponic recirculation and condensate reuse to offset regional water scarcity. Strong solar irradiance and decentralized infrastructure in North Africa justify the emphasis on PV integration and modular system design.

Table 3 summarizes the proposed performance metrics for vertical wheat production in arid climates, contrasting current benchmarks with target values adapted to North-African contexts. These indicators integrate energy, cost, and resource-efficiency metrics to guide system-level optimization.

Table 3. Proposed performance metrics for vertical-wheat farming in arid climates.

Dimension	**Current benchmark**	**Target benchmark (arid North Africa)**	**Evaluation focus**
Energy use	300–400 kWh t^{-1} biomass	≤ 250 kWh t^{-1} biomass	Renewable share; waste-heat recovery
Production cost	> 1 000 USD t^{-1} (Pilot studies)	≤ 500 USD t^{-1} by 2030	Cost per tonne vs. import price
Energy share of OPEX	50–60 %	≤ 40 %	Tariff sensitivity; efficiency gains
Water use	70–80 % reduction (Current CEA)	≥ 90 % reduction	Hydroponics; condensate reuse
CO_2 recycling	< 30 %	≥ 70 %	Industrial symbiosis; capture systems
Land intensity	5–10× field yield	≥ 10–20× field yield	m^2 footprint per tonne
Resilience	Case-specific pilots	Modular; grid-independent; scalable	Food security; adaptation potential

Source: United Nations [31], Zhu and Marcelis [5], Asseng et al. [4], Al-Ghawas [12], Ali [16]; FAO [28], and Manceron et al. [9].

3.4. Implementation Roadmap for Vertical Wheat in Arid Climates

The proposed control strategy should be viewed as a flexible blueprint that can be adapted to different facility scales, policy environments, and technological developments. In the short term (2025–2030), pilot facilities can demonstrate technical feasibility at reduced, though still elevated, production costs. These facilities would rely on research funding, innovation grants, and targeted subsidies to support early deployment. In the medium term (2030–

2040), economies of scale, expanded renewable-energy integration, and industrial CO_2-capture partnerships could progressively lower production costs toward parity with imported wheat [7, 8].

By 2040–2050, with strong renewable-energy policies, carbon-pricing mechanisms, and agri-innovation programmes, combined with continued advances in LED efficiency, CO_2 management, and hydroponic system design, vertical-wheat facilities could serve as strategic buffers within national food systems. Their role would be to maintain stable domestic wheat supplies during droughts, trade disruptions, or geopolitical shocks, complementing conventional imports through decentralised, solar-powered production clusters [9, 12].

Risks include energy-price volatility, high capital expenditure (CAPEX), and uncertain long-term policy support. However, opportunities for alignment with national solar programmes, water-security strategies, and climate adaptation objectives suggest that vertical wheat farming could evolve into both a food-security instrument and a climate-resilience mechanism for arid-region economies [1-3].

4. IMPLEMENTATION CONSTRAINTS AND CHALLENGES

Although vertical wheat farming presents a promising pathway for enhancing food security in arid climates, particularly in North Africa, its practical implementation faces multiple constraints. These challenges span technical, economic, environmental, and institutional domains, highlighting the gap between conceptual strategies and operational feasibility.

4.1. Technical and Infrastructural Barriers

A primary challenge is the high energy intensity of vertical wheat farming. As outlined in Section 3, renewable energy integration and efficiency measures can reduce consumption, yet the baseline demand for lighting and cooling remains substantial. Unlike leafy greens, wheat requires extended photoperiods with moderate-to-high light intensity and continuous climate control across long growth cycles (≈70–120 days), significantly increasing energy demand [4, 5]. Even with large-scale photovoltaic deployment, intermittency and storage requirements remain limiting factors in North Africa, where grid reliability varies widely [12].

Water infrastructure presents a second constraint. Although vertical farms can recycle more than 90% of their water, closed-loop hydroponic systems require high-quality input water and advanced sanitation to prevent pathogen accumulation. In many North African urban areas, water supply is scarce or costly, raising concerns about both start-up feasibility and long-term operational <<resilience>> [28]. Additionally, deploying the sophisticated HVAC and dehumidification systems required for cereal crops necessitates technical expertise and reliable supply chains, elements not consistently available across the region [21].

CO_2 supply and distribution constitute a further barrier. While industrial CO_2 sources exist, for example, cement plants in Algeria and Morocco, the capture, purification, and transport of CO_2 for agricultural enrichment require infrastructure investment and regulatory oversight [29]. In the absence of such systems, reliance on imported compressed CO_2 increases operational costs and carbon intensity.

4.2. Economic and Financial Constraints

The most significant barrier to vertical wheat farming in arid climates is economic viability. Current production costs are estimated at three to five times the global market price, with energy accounting for up to 70% of expenditures [5, 12]. In North Africa, where imported wheat costs approximately 250–300 USD t^{-1} [7, 8], producing wheat indoors at more than 1,000 USD t^{-1} remains commercially prohibitive. Even with economies of scale, expanded renewable-energy adoption, and targeted policy incentives, projections suggest production costs may decline only to 500–600 USD t^{-1} by 2030 [4, 13].

Financing such systems presents additional challenges. Large-scale vertical-wheat facilities require capital expenditures in the tens of millions of USD for land acquisition, construction, equipment, and energy systems [31].

Attracting investors is difficult given the uncertain profitability and high perceived risk, especially in food-import-dependent economies where competing public priorities are substantial. Without blended-finance models, combining government incentives, private-sector investment, and development agency funding, the sector is unlikely to reach commercial maturity [9].

4.3. Environmental and Sustainability Constraints

While vertical farming is often positioned as a sustainable alternative to traditional agriculture, several environmental limitations must be acknowledged. The <<dependence>> on electricity-intensive systems can result in significant indirect carbon emissions when local grids remain dominated by fossil fuels, as is the case across much of North Africa [1]. Without a substantial expansion of renewable energy, indoor wheat production may inadvertently undermine its own climate-resilience objectives.

Physiological limitations also apply. Even under optimized indoor conditions, enhanced CO_2, tailored spectra, and extended photoperiods, wheat exhibits diminishing returns beyond certain thresholds, and grain-protein dilution remains a recurrent issue [26, 29]. This suggests that highly controlled systems may not always achieve the nutritional quality required for a staple crop.

Waste management presents another environmental concern. Although hydroponics reduces soil-borne diseases, nutrient-rich effluents must be treated or reused safely. Inadequate disposal could create secondary environmental risks, particularly in water-scarce settings [16].

4.4. Socio-Political and Institutional Challenges

Beyond technical and economic barriers, vertical wheat farming faces significant institutional constraints. Many North African countries lack regulatory frameworks governing controlled-environment agriculture, complicating CO_2 sourcing, renewable energy integration, and biosafety compliance [2]. Food security strategies in the region have historically prioritized subsidized imports rather than stimulating domestic production, creating structural disincentives for investment in innovative cultivation systems [7, 8]. Moreover, subsidized electricity and water prices distort true resource costs, making it difficult to establish a realistic business case without substantial policy reform.

Social acceptance is an additional consideration. While urban consumers may welcome locally produced, climate-resilient foods, perceptions of "unnatural" production methods or higher prices may limit market uptake. Building consumer trust will require transparency regarding safety, nutritional quality, and the role of controlled-environment agriculture within broader food-system policies [9].

5. DISCUSSION

The findings of this study highlight both the transformative potential and the persistent limitations of vertical wheat farming in arid zones. A central contribution lies in integrating physiological insights with technological capabilities to develop a context-specific control strategy, followed by an assessment of implementation barriers. Taken together, these analyses demonstrate that although vertical farming could theoretically strengthen food security in North Africa, substantial technical, economic, and policy constraints must be addressed before it can meaningfully contribute to national wheat supply.

A primary theme concerns the tension between agronomic optimization and economic viability. Controlled-environment agriculture enables precise regulation of light, CO_2, temperature, and humidity, often producing yields several times higher than those of open-field systems [4, 6]. However, these gains are counterbalanced by the exceptionally high energy and infrastructure costs associated with cereal production in indoor systems, particularly when compared with short-cycle crops such as leafy greens [12]. As noted earlier, indoor wheat production costs remain at least three to five times higher than global market prices [5, 12]. This suggests that, in the medium term, vertical wheat farming is unlikely to compete directly with imports on price. Instead, it may serve strategic or niche roles, acting as a buffer during supply chain disruptions or producing premium wheat varieties for domestic markets.

A second key finding concerns the centrality of energy systems. Section 3 showed that lighting and cooling dominate total energy demand, while Section 4 highlighted that many North African grids remain heavily fossil-fuel dependent [1]. Without strong coupling to renewable energy generation, vertical farms risk undermining their own sustainability rationale and becoming vulnerable to volatile electricity prices. Their long-term viability, therefore, depends not only on advances in agricultural optimization but also on national progress in renewable energy infrastructure, storage technologies, and grid reliability [9, 29].

Water use presents a contrasting narrative. Vertical farms can reduce water consumption by up to 95% compared with open-field production [16, 21]. This is a particularly significant advantage in North Africa, where water scarcity is a major driver of agricultural instability. Integrating closed-loop hydroponics and condensate recovery can therefore yield genuine sustainability gains. However, as Section 4 noted, reliance on purified inputs and pathogen-free recirculation infrastructure introduces hidden vulnerabilities, necessitating continuous monitoring and maintenance. As such, the conversation shifts from water sufficiency to water-quality management, which will be decisive for stable long-term operation.

Nutritional and quality outcomes represent another critical dimension. Although elevated CO_2 and optimized light regimes can boost biomass yields, several studies indicate grain-protein dilution when nitrogen is not managed appropriately [26, 29]. In regions where wheat provides a major share of dietary protein, such quality reductions could undermine food security objectives even if caloric yields increase. Future research must therefore balance yield targets with nutritional adequacy to ensure that indoor-grown wheat meets or exceeds the quality of field-grown imports.

At the systems level, vertical wheat farming should be viewed as complementary, rather than substitutive, to conventional agriculture. Field production will remain indispensable, but vertical farms could serve as strategic buffers against climate shocks, geopolitical disruptions, and chronic water scarcity [2, 7, 8]. Their strategic value parallels that of energy diversification: contribution is measured not only in tonnage but in supply-chain resilience during crises.

Policy and governance factors are equally decisive. Without targeted subsidies, renewable-energy incentives, and clear regulations for CO_2 sourcing and biosafety, vertical wheat farming will remain economically prohibitive [8, 9]. Conversely, embedding such systems within national food security strategies, similar to emerging initiatives in the Gulf region, could attract blended finance and accelerate technological diffusion [9]. Institutional alignment, regulatory clarity, and innovation funding are therefore as critical as agronomic optimization.

Finally, this study identifies several research frontiers. Much of the current evidence on vertical wheat production remains experimental, with gaps related to optimal light spectra, CO_2 scheduling algorithms, genotype-specific responses, and multi-tier airflow dynamics [12, 21]. Bridging these gaps and translating pilot-scale insights into commercially scalable protocols will require interdisciplinary collaboration among plant scientists, engineers, economists, and policymakers. Given the global importance of wheat, advances in this frontier could reshape cereal production paradigms across multiple climate-stressed regions.

Overall, vertical wheat farming in arid climates exists at the intersection of technological promise and systemic constraints. Its advantages lie in resilience, water efficiency, and controlled productivity, yet its challenges, particularly high energy demand and elevated production costs, remain formidable. Addressing these barriers will require integrated solutions across agricultural, energy, and policy domains. Rather than functioning as a "silver bullet," vertical wheat farming should be understood as one component within a diversified food-security strategy that complements field agriculture and enhances resilience against the escalating challenges facing arid-zone food systems.

6. CONCLUSION AND FUTURE DIRECTIONS

This study developed an integrated environmental-control framework for vertical wheat farming in arid climates, linking lighting, CO_2 enrichment, and indoor-climate regulation to techno-economic performance. The framework moves beyond single-parameter optimization and demonstrates how coordinated environmental control can simultaneously improve crop yield, energy efficiency, and cost-effectiveness under severe resource constraints [5, 12].

The findings confirm that electricity use, particularly for lighting and cooling, defines the principal feasibility boundary for cereal-scale vertical farms, typically accounting for 60–70% of total operating costs [9]. By integrating renewable energy, waste-heat recovery, and adaptive scheduling, the proposed strategy can reduce energy-use intensity to below 250 kWh t^{-1} of biomass, compared with the 300–400 kWh t^{-1} reported in existing pilot studies [21, 31]. When combined with water recycling, condensate recovery, and CO_2 circularity, these measures enhance sustainability outcomes by reducing freshwater withdrawals and embedded emissions. Such efficiency targets are especially relevant for arid economies, including those of North Africa, where high ambient temperatures, chronic water scarcity, and carbon-intensive grids necessitate stricter performance benchmarks [2, 8].

Four key performance indicators (KPIs) emerge as critical levers linking environmental parameters to techno-economic viability.

1. Energy-use efficiency (EUE) — total energy consumption per tonne of biomass.
2. Water-recycling rate (WRR) — proportion of recovered and reused water.
3. CO_2-use efficiency (CUE) — effective CO_2 uptake relative to supplied enrichment.
4. Yield-to-cost ratio (YCR) — grain output per unit of operating expenditure.

Achieving these KPIs requires dynamic coordination among lighting, HVAC, and nutrient subsystems through a unified control logic. The integrated strategy thus offers a replicable blueprint for the design and optimization of future vertical-wheat facilities operating in hot-arid environments.

Future research should prioritize pilot-scale validation of the proposed framework, incorporating real-time sensing, model-predictive control, and digital-twin architectures to evaluate energy–yield–quality trade-offs. Coupling the environmental-control model with crop-growth simulators (e.g., DSSAT or APSIM) and life-cycle assessment (LCA) tools would enable a more comprehensive evaluation of resilience, scalability, and carbon performance [26, 29]. Additionally, aligning pilot facilities with national renewable-energy and food-security programmes could accelerate policy integration and attract private-sector investment.

In conclusion, this study demonstrates that vertical wheat farming in arid climates exists at the intersection of technological feasibility and systemic constraints. By articulating how environmental parameters can be optimized jointly within techno-economic limits, the study outlines a scalable pathway towards climate-resilient, resource-efficient wheat production in water-scarce regions worldwide.

Funding: This study received no specific financial support.
Institutional Review Board Statement: Not applicable.
Transparency: The authors state that the manuscript is honest, truthful, and transparent, that no key aspects of the investigation have been omitted, and that any differences from the study as planned have been clarified. This study followed all writing ethics.
Competing Interests: The authors declare that they have no competing interests.
Authors' Contributions: Both authors contributed equally to the conception and design of the study. Both authors have read and agreed to the published version of the manuscript.

REFERENCES

[1] Intergovernmental Panel on Climate Change (IPCC), *Climate change 2023: Synthesis report*. Geneva, Switzerland: IPCC, 2023.

[2] Food and Agriculture Organization of the United Nations (FAO), *Near East and North Africa – regional overview of food security and nutrition 2023*. Cairo, Egypt: FAO, 2023.

[3] F. Kalantari, O. M. Tahir, A. M. Lahijani, S. Kalantari, M. F. M. Zain, and S. Javed, "Sustainability aspects of controlled-environment agriculture: Energy, water, and food nexus," *Journal of Cleaner Production*, vol. 292, p. 126067, 2021.

[4] S. Asseng *et al.*, "Wheat yield potential in controlled-environment vertical farms," *Proceedings of the National Academy of Sciences*, vol. 117, no. 32, pp. 19131-19135, 2020. https://doi.org/10.1073/pnas.2002655117

[5] X.-G. Zhu and L. Marcelis, "Vertical farming for crop production," *Modern Agriculture*, vol. 1, no. 1, pp. 13-15, 2023. https://doi.org/10.1002/moda.4

[6] X. Shen, Y. Zhang, J. Li, L. Wu, and W. Chen, "Energy optimisation and thermal modelling in multi-layer wheat plant factories," *Frontiers in Plant Science*, vol. 15, p. 145601, 2024.

[7] K. Horri, "Importance of the food issue in Algeria's economic policy," *International Journal of Nutrition and Food Sciences*, vol. 13, no. 2, pp. 13–19, 2024. https://doi.org/10.11648/j.ijnfs.20241302.11

[8] U.S. Department of Agriculture Foreign Agricultural Service, *Grain and feed annual: Algeria 2025*. Washington, DC: USDA, 2025.

[9] S. Manceron, E. Marajo-Petitzon, M. A. Caillaud, A. Forslund, and C. Le Mouël, "Can the middle East–North Africa region mitigate the rise of its food import dependency under climate change?," *Regional Environmental Change*, vol. 23, no. 2, p. 52, 2023.

[10] K. Al-Kodmany, "The vertical farm: A review of developments and implications for the vertical city," *Buildings*, vol. 8, no. 2, p. 24, 2018. https://doi.org/10.3390/buildings8020024

[11] N. Kozai, *Resource use efficiency in plant factories with artificial lighting*. Cham, Switzerland: Springer Nature, 2019.

[12] D. Al-Ghawas, *Are vertical farms the only way to future-proof agriculture in the Middle East?* United Arab Emirates: Fast Company Middle East, 2024.

[13] Bustanica, *World's largest vertical farm launched in Dubai*. Dubai: Bustanica, 2022.

[14] D. Despommier, *The vertical farm: Feeding the world in the 21st century*. United States: Picador, 2020.

[15] J. Eichelsbacher, "Environmental control effects on wheat productivity in fully enclosed systems," *Agronomy*, vol. 15, no. 2, pp. 255-268, 2025.

[16] M. Ali, "Nitrogen management in wheat: Current status and future strategies," *Frontiers in Plant Science*, vol. 12, p. 778360, 2021.

[17] X. Bao *et al.*, "Single irrigation at the four-leaf stage in the spring optimizes winter wheat water consumption characteristics and water use efficiency," *Scientific Reports*, vol. 12, no. 1, p. 14257, 2022. https://doi.org/10.1038/s41598-022-18446-8

[18] S. G. Chavan, R. A. Duursma, M. Tausz, and O. Ghannoum, "Elevated CO2 alleviates the negative impact of heat stress on wheat physiology but not on grain yield," *Journal of Experimental Botany*, vol. 70, no. 21, pp. 6447-6459, 2019. https://doi.org/10.1093/jxb/erz386

[19] H. Clauw *et al.*, "The impact of a six-hour light–dark cycle on wheat ear emergence, grain yield, and flour quality in future plant-growing systems," *Foods*, vol. 13, no. 5, p. 750, 2024. https://doi.org/10.3390/foods13050750

[20] F. Orsini, M. Rinaldi, S. De Pascale, A. Maggio, and P. Santamaria, "Resource-use efficiency of indoor lettuce cultivation under different hydroponic systems," *Agricultural Water Management*, vol. 228, p. 105791, 2020.

[21] R. M. Wheeler, C. L. Mackowiak, J. C. Sager, W. M. Knott, and C. R. Hinkle, "Growing wheat in a NASA advanced life support system," *Life Support and Biosphere Science*, vol. 2, no. 4, pp. 179–187, 1996.

[22] H. Sheehan and A. Bentley, "Changing times: Opportunities for altering winter wheat phenology," *Plants, People, Planet*, vol. 3, no. 2, pp. 113-123, 2021. https://doi.org/10.1002/ppp3.10163

[23] K. Harris, P. Martin, and H. Eagles, "Environmental responses of wheat regarding photoperiod," *Field Crops Research*, vol. 188, pp. 71–77, 2016.

[24] M. Farhad *et al.*, "GWAS for early-establishment QTLs and their linkage to major phenology-affecting genes (Vrn, Ppd, and Eps) in bread wheat," *Genes*, vol. 14, no. 7, p. 1507, 2023. https://doi.org/10.3390/genes14071507

[25] A. S. Virdi, N. Singh, K. K. Bains, and A. Kaur, "Effect of photoperiod and growth media on yield and antioxidant properties of wheatgrass juice of Indian wheat varieties," *Journal of Food Science and Technology*, vol. 58, no. 8, pp. 3019-3029, 2021. https://doi.org/10.1007/s13197-020-04805-8

[26] X. Wang and L. Liu, "Effects of elevated CO_2 on grain yield and quality in different wheat cultivars," *Journal of Cereal Science*, vol. 100, p. 103232, 2021.

[27] Q. Yang, Y. Gong, J. Shi, and J. Deng, "Optimising vertical-farm conditions for wheat cultivation under climate-change scenarios," *Sustainability*, vol. 15, no. 3, p. 2104, 2023.

[28] FAO, "Water use efficiency in arid regions," FAO Water Reports, No. 48, Rome, Italy, 2022.

[29] J. Yang *et al.*, "Mitigation of elevated CO2 concentration on warming-induced changes in wheat is limited under extreme temperature during the grain filling period," *Agronomy*, vol. 13, no. 5, p. 1379, 2023. https://doi.org/10.3390/agronomy13051379

[30] C. Zulkosky, *Infarm grows wheat indoors in food-security breakthrough*. United States: The Food Institute, 2022.

[31] United Nations, *Transforming food systems for sustainable development: SDG 2 and SDG 13 synergies*. New York: UN Department of Economic and Social Affairs, 2023.