Multi-Tier Cultivation Units in Protected Ground: A Systematic Review of Construction Types, Resource Performance and the Normative Coverage Gap

Sh.Kh.Juraboev
"Tashkent Institute of Irrigation and Agricultural Mechanization Engineers" National Research University

Abstract: *Purpose. Multi-tier (vertical) cultivation units are consolidating into an independent class of protected-ground engineering, yet research attention and normative regulation remain concentrated on the industrial end of the size spectrum. This review aims to systematise the construction types of multi-tier cultivation units, to consolidate their technological and resource-use indicators on a common scale, and to quantify - rather than merely assert - the gap in the normative framework that applies to small-volume units. Methods. A critical-analytical review was carried out on four source groups: international peer-reviewed literature, the engineering school of the CIS countries, national legal and building-code documents of Uzbekistan, and EN, ISO and ANSI/ASABE standards. Protected-ground facilities were classified by nine independent attributes expressed as a classification vector; four construction classes were compared across nine indicators; covering materials were compared by light transmittance, heat transfer coefficient and service life; and eleven normative documents were assessed against eight criteria on a three-level scale, with a coverage index computed for each criterion. Results. Four development stages of protected-ground engineering were distinguished, revealing that the number of controlled factors and the specific energy consumption per unit of product have grown together. Multi-tier closed systems increase yield by a factor of 11 ± 1.7 (41 ± 6.1 versus 3.9 ± 0.21 $kg \cdot m^{-2} \cdot year^{-1}$) and reduce water use by approximately 13 times (20 ± 3.8 versus 250 ± 25 $L \cdot kg^{-1}$), but consume 82 ± 11 times more energy (90 000 ± 11 000 versus 1 100 ± 75 $kJ \cdot kg^{-1}$). The coverage analysis returned an index of 27.3 % for structural design and for air-exchange calculation, 18.2 % for photosynthetic radiation quantities, 9.1 % for irrigation hardware, and exactly 0 % for four criteria: inter-tier temperature difference, air velocity above the canopy, illumination non-uniformity, and applicability to small-volume multi-tier constructions. Conclusions. The intersection of "multi-tier, sole-source artificial lighting, small-volume, fully automated, building-integrated" is the least covered cell of the classification space in both the literature and the normative base. Eight verifiable indicators are proposed for a sectoral normative document, including $\Delta T < 2$ °C, air velocity 0.3-1.0 $m \cdot s^{-1}$, PPFD 150-250 $\mu mol \cdot m^{-2} \cdot s^{-1}$, DLI 12-17 $mol \cdot m^{-2} \cdot day^{-1}$ and illumination non-uniformity below 20 %.*

Keywords: *protected ground, multi-tier cultivation unit, plant factory with artificial lighting, vertical farming, classification, microclimate uniformity, inter-tier temperature gradient, PPFD, daily light integral, normative coverage index*

1. Introduction

Protected-ground facilities are engineering structures that shield plants from adverse external conditions and create an artificial microclimate for them. Their engineering task is to hold air and substrate temperature, humidity, photosynthetically active radiation and carbon dioxide concentration within required limits throughout the growing period. Hanan formulated this in explicitly engineering terms, defining a greenhouse as an environment-forming device in which human-controlled factors are given precedence over natural ones [1]. Read as a design criterion rather than a definition, this statement frames the entire history of the field as a progressive substitution of natural factors by controlled ones.

Where arable land is limited, irrigation water is scarce and urbanisation is rapid, multi-tier (vertical) cultivation systems are increasingly regarded as a strategic direction. Their conceptual foundation was formulated by Despommier, who argued that growing food inside multi-storey urban buildings is not only technically feasible but an unavoidable response to urban population growth [3]. The direction was subsequently developed on an engineering basis by Kozai and colleagues, and plant factories with artificial lighting (PFALs) emerged as an independent technical class with their own resource-efficiency metrics, climate-control architecture and design methodology [4, 5, 6].

The development of protected-ground engineering can be divided into four stages, and the sequence of these stages exposes a pattern that motivates the present work: with each transition the number of controlled factors increased, and so did the specific energy consumption per unit of product. This defines the central contradiction of the field - an improvement in control quality must not be paid for by an increase in energy consumption. The contradiction is sharpest at the small end of the size spectrum, because centralised air-handling units, heat recovery and large thermal buffers, which industrial facilities use to resolve it, are economically unjustifiable in units of a few square metres.

Research effort in the field is strongly polarised. At one pole, industrial-scale plant factories have been studied in depth: resource-use efficiency has been quantified against greenhouses under a common methodology [7], energy demand has been analysed as a function of façade design [8], airflow uniformity has been optimised numerically [15], and the economics of load shifting have been evaluated [11]. At the other pole, units intended for domestic and small-scale use are developed as commercial products rather than as research objects; their constructive and technological parameters, air flow rates and energy balances are not published and have not been independently verified. The consequence is that miniaturisation is performed by simply scaling down industrial solutions, whereas the underlying microclimate processes do not scale linearly: as the enclosed volume shrinks, the volumetric heat load rises, the air circulation path shortens, and the temperature gradient concentrates between tiers rather than being dissipated.

A parallel gap exists on the regulatory side. Design and operation of protected-ground facilities are governed by three tiers of documents - national, intergovernmental and international - all of which were written for stand-alone, large-area, naturally lit structures. Whether this legacy orientation leaves the small multi-tier class genuinely unregulated, and to what extent, has not previously been assessed quantitatively; the claim is usually made in narrative form, without a reproducible measure.

The aim of this review is therefore threefold: (i) to systematise the constructions of multi-tier cultivation units and to place the small-volume, fully automated, sole-source lighting unit precisely within a formal classification space; (ii) to consolidate published technological and resource-use indicators for the class on a common scale and to expose the trade-offs between constructive parameters; and (iii) to quantify the coverage of the current normative base by means of a coverage matrix and a coverage index, and to translate the identified gaps into a set of verifiable indicators suitable for a sectoral standard.

The novelty of the work lies in three elements. First, the classification of protected-ground facilities by nine independent attributes is formalised as a vector, which makes the “empty cells” of the classification space explicit rather than rhetorical. Second, the mutually opposing effects of constructive parameters on technological indicators are consolidated in a single analytical table, from which recommended ranges for a small-volume unit are derived. Third, a coverage-index methodology for normative documents is proposed and applied, producing numerical evidence that four design-critical criteria of multi-tier units are covered by none of the analysed documents.

2. Materials and Methods

2.1. Object of the review

The object of the review is twofold: the constructive schemes of multi-tier cultivation units used in protected ground, and the body of normative documents governing their design and operation. As a concrete anchor for the analysis, a three-tier mini-greenhouse protected by utility-model patent FAP 2882 of the Republic of Uzbekistan was used: width 1200 mm, depth 500 mm, height 2400 mm, with air admitted from below through a left-hand duct, moving upward along the tiers and discharged through a right-hand duct. This anchor was chosen because it represents the extreme small-volume case, in which no centralised air-handling equipment is present and the microclimate is formed by fans alone.

2.2. Source base and inclusion criteria

Four source groups were analysed. (a) International peer-reviewed literature and monographs on plant factories, vertical farming, climate uniformity and resource-use efficiency. (b) The engineering literature and dissertations of the CIS school of protected-ground technology. (c) National legal acts, presidential and governmental resolutions and building codes (ShNQ) of the Republic of Uzbekistan. (d) Intergovernmental (SP, GOST, RD-APK) and international (EN, ISO, ANSI/ASABE) standards.

For scientific sources the inclusion criteria were: publication between 1995 and 2025; direct relevance to multi-tier closed systems, microclimate uniformity, lighting regime or resource consumption; and the presence of quantitative results or a validated model. For normative documents the inclusion criterion was the presence of a requirement or a calculation procedure applicable to protected-ground facilities, their microclimate, their lighting or their irrigation hardware. Sources reporting only qualitative or commercial claims without a reproducible measurement basis were excluded.

2.3. Classification methodology

Nine mutually independent attributes were adopted for classifying a protected-ground facility, and the position of a facility within the classification space was expressed as a vector:

$$K = \{k1, k2, k3, k4, k5, k6, k7, k8, k9\} \quad (1)$$

where k1 is the purpose of the facility; k2 - its construction type; k3 - the covering material; k4 - the heating method; k5 - the light source; k6 - the cultivation technology; k7 - the level of automation; k8 - the operating floor area; k9 - the siting. Within each attribute the types form mutually exclusive classes, so that any facility corresponds to a single point of the classification space. This formalisation is what allows a distinction to be drawn between intersections that are well represented in the literature and intersections that are not.

2.4. Comparison metrics

Four construction classes were compared using a single set of nine indicators: usable floor area, number of tiers, lighting type, microclimate-control method, irrigation scheme, control level, staffing requirement, specific investment, and the dominant technological constraint. Covering materials were compared by light transmittance, heat transfer coefficient and service life.

The principal benefit of multi-tier arrangement is expressed as the floor-area multiplication factor:

$$Kf = n \cdot Ay / Ab \quad (2)$$

where Kf is the floor-area multiplication factor; n - the number of tiers; Ay - the usable area of one tier, m^2; Ab - the footprint area occupied by the unit, m^2.

The inter-tier spacing is the sum of three components:

$$hy = hlum + hz + hmax \quad (3)$$

where hy is the spacing between tiers, mm; hlum - the height of the luminaire, mm; hz - the required clearance between the luminaire and the plant apex, mm; hmax - the maximum plant height, mm.

The inter-tier temperature non-uniformity is defined as the difference between the air temperature of the uppermost and the lowest tier:

$$\Delta T = Tn - T1 \quad (4)$$

where ΔT is the temperature non-uniformity, °C; Tn - the air temperature of the uppermost (n-th) tier, °C; T1 - the air temperature of the lowest tier, °C.

Spatial uniformity of a microclimate variable was assessed by the coefficient of variation:

$$CV = (S / \bar{x}) \cdot 100\ \% \quad (5)$$

where CV is the coefficient of variation, %; S - the standard deviation across the measurement points; $\bar{x}$ - the mean value of the variable over all measurement points. This metric was used to bring the airflow and humidity distribution results of different authors onto a common scale.

The lighting regime was expressed through photon quantities rather than photometric ones:

$$DLI = PPFD \cdot \tau f \cdot 3600 \cdot 10^{-6} \quad (6)$$

where DLI is the daily light integral, $mol \cdot m^{-2} \cdot day^{-1}$; PPFD - the photosynthetic photon flux density, $\mu mol \cdot m^{-2} \cdot s^{-1}$; τf - the photoperiod, h. This choice follows ANSI/ASABE S640 [27], in which the photon flux density in the 400-700 nm waveband is defined as the primary quantity for evaluating radiation incident on plants; the lux, being weighted by the spectral sensitivity of the human eye, is unsuitable for that purpose.

2.5. Coverage analysis of normative documents

Normative documents were grouped into three levels - national (Uzbekistan), intergovernmental (CIS) and international. A total of M = 11 documents, or thematically coherent document groups, entered the analysis. Each was assessed against eight criteria: K1 - structural design and loads; K2 - air-exchange calculation methodology; K3 - photosynthetic radiation quantities (PPFD, DLI); K4 - permissible inter-tier temperature difference; K5 - air velocity above the plant canopy; K6 - illumination non-uniformity; K7 - requirements for irrigation hardware; K8 - direct applicability to small-volume (< 100 m²) multi-tier constructions.

A three-level scale was used: "+" - the criterion is specified with a numerical value or a verifiable requirement; "±" - the criterion is addressed indirectly, in general terms, or for a different object; "–" - the criterion is not addressed. For each criterion a coverage index was computed:

$$Ik = (mk / M) \cdot 100\ \% \quad (7)$$

where Ik is the coverage index for criterion k, %; mk - the number of documents addressing that criterion at the "+" level; M - the total number of documents analysed. A partial-coverage index Ik± was computed by the same expression, counting "+" and "±" ratings together.

2.6. Data processing and reporting

Numerical values taken from heterogeneous sources were converted to a common set of units: yield in $kg \cdot m^{-2} \cdot year^{-1}$, water consumption in $L \cdot kg^{-1}$, energy consumption in $kJ \cdot kg^{-1}$ and electrical productivity in $kg \cdot (kW \cdot h)^{-1}$. Standard deviations reported by the original authors were preserved unchanged. Because the study is a review, no new experiments were performed and no new numerical values were introduced: every quantitative indicator reported below belongs to the cited sources, while the coverage indices follow directly and reproducibly from the coverage matrix.

3. Results

3.1. Development stages and the underlying pattern

Four stages of protected-ground engineering were distinguished. In the first stage (late nineteenth century to the first half of the twentieth) glass-covered, naturally lit, water-heated structures were built. In the second stage (1960s-1980s) industrial block greenhouse complexes with automated ventilation and heating were introduced, and the theoretical foundations of protected-ground engineering were laid in the CIS countries [29]. In the third stage (from the 1990s) small-volume substrate cultivation, drip irrigation and computerised climate control became widespread [2, 25]. In the fourth, current stage, natural light has been abandoned entirely and multi-tier, artificially lit units - plant factories - have taken shape [3, 4, 5].

Comparing the stages reveals a monotonic pattern: as the number of controlled factors grew, so did the specific energy consumption per unit of product. This is the central contradiction addressed by contemporary research in the field, and it is the reason why energy-related criteria dominate the recent literature on vertical farming [9, 11].

3.2. The classification system and the position of the review object

The systematised classification derived from expression (1) is presented in Table 1.

Table 1.

Classification of protected-ground facilities by nine independent attributes

Attribute	Symbol	Types
Purpose	k1	vegetable production, transplant raising, floriculture, research
Construction type	k2	span (arch) type, block type, tunnel, rack (multi-tier), container type
Covering material	k3	glass, polycarbonate, polyethylene film, combined
Heating method	k4	solar (unheated), technically heated, combined
Light source	k5	natural light, supplemental lighting, sole-source artificial lighting (PFAL)
Cultivation technology	k6	soil-based, small-volume substrate, hydroponic (NFT, DWC), aeroponic
Level of automation	k7	manual, partially automated, fully automated
Operating floor area	k8	industrial (> 1000 m²), farm-scale (100-1000 m²), small-volume and domestic (< 100 m²)
Siting	k9	free-standing, building-integrated, mobile (container type)

Applying expression (1) to the review object yields the vector: rack (multi-tier) construction; combined polycarbonate and tempered-glass covering; sole-source artificial lighting; small-volume substrate cultivation; full automation; small-volume floor area; building-integrated siting. The intersection of these seven attribute values constitutes the least studied class in the literature: industrial-scale plant factories are well covered [4, 6, 7], whereas units designed for domestic conditions are developed as commercial products whose parameters are not published.

3.3. Functional structure of a multi-tier unit

The construction of a multi-tier unit resolves into five functional groups: the load-bearing frame, the enclosing envelope, the tier (rack) system, the engineering systems (irrigation, ventilation, lighting) and the control unit.

Aluminium profile as the frame material makes the unit demountable and keeps its mass low. In industrial greenhouses the frame loads are governed by snow and wind actions [26, 29]; in a small-volume, building-integrated unit these actions are absent altogether, and the governing load is the mass of substrate, water and plants, amounting to a distributed load of 30-50 kg per tier in a three-tier unit. This figure is the basis for selecting the profile cross-section, and it differs from the industrial design case not by magnitude alone but in kind, since it is a permanent gravity load rather than a variable environmental action.

The tier system is the defining constructive element: a luminaire is mounted beneath each tier and plant containers stand above it. Following expression (3), the spacing for leafy crops is typically 350-450 mm.

A characteristic feature of the reviewed configuration is that air enters from below through a left-hand duct, travels upward along the tiers and is discharged through a right-hand duct. This scheme dispenses with a centralised air-handling unit and simplifies the construction, but because the air stream absorbs additional heat at every tier it inherently generates a vertical temperature gradient - the very quantity defined by expression (4).

3.4. Comparison of covering materials

The principal indicators of covering materials are summarised in Table 2.

Table 2.

Comparative characteristics of covering materials for protected-ground facilities

Material	Light transmittance, %	Heat transfer coefficient, $W \cdot m^{-2} \cdot K^{-1}$	Service life, years	Characteristics
Silicate glass (4 mm)	88-90	5.8-6.0	25 and more	high transparency, heavy, brittle
Tempered glass	86-89	5.6-5.9	25 and more	impact resistant, expensive
Twin-wall polycarbonate (8 mm)	78-82	3.0-3.4	10-15	good insulation, light, UV-protected
Triple-wall polycarbonate (16 mm)	70-75	2.2-2.5	10-15	best insulation, high light loss
Polyethylene film	80-88	6.5-7.5	2-4	inexpensive, ages rapidly

The data expose an inherently opposed pair of properties: as light transmittance falls from 88-90 % to 70-75 %, that is by a factor of about 1.2, the heat transfer coefficient falls from 5.8-6.0 to 2.2-2.5 $W \cdot m^{-2} \cdot K^{-1}$, that is by a factor of 2.4. In naturally lit structures the two requirements therefore compete, and the choice of material is a compromise. In a sole-source-lighting unit the competition disappears: light enters from an internal source, envelope transmittance loses its design significance, and the material can be selected unambiguously on the insulation criterion. What becomes important instead is the reflectance of the internal surfaces, because reflected photons re-enter the canopy and contribute to photosynthesis.

In the reviewed unit a combination is used: the front door is tempered glass, so that the user can observe the plants, while the remaining surfaces are polycarbonate. Internal surfaces carry a reflective finish.

3.5. Comparison of multi-tier unit classes

Multi-tier units in current practice were divided into four groups by overall dimensions and field of application; their comparison is given in Table 3.

Table 3.

Comparative characteristics of multi-tier cultivation unit classes

Indicator	Industrial PFAL	Container farm	Laboratory rack	Domestic unit
Usable area, m^2	> 500	25-35	5-20	2-6

Number of tiers	8-16	4-8	3-6	2-4
Lighting	LED, sole source	LED	LED or fluorescent	LED
Microclimate control	centralised air handling	split system	fan	fan
Irrigation	hydroponics with recirculation	NFT or DWC	manual or drip	drip
Control	SCADA, artificial intelligence	controller and IoT	timer	timer or controller
Operating personnel	agronomist and engineer	operator	laboratory assistant	not required
Specific investment	very high	high	medium	low
Dominant constraint	energy consumption	climate non-uniformity	lighting gradient	control quality

Table 3 shows that as the usable area contracts by more than two orders of magnitude, from above 500 m² to 2-6 m², the microclimate-control means degrade from a centralised air-handling unit to a single fan and the control level from SCADA to a timer. Critically, the dominant constraint also migrates: in industrial systems it is energy consumption, whereas in domestic units it becomes control quality. The number of tiers falls from 8-16 to 2-4, so that the multiplication factor Kf of expression (2) is reduced roughly fourfold, which weakens the very advantage for which the multi-tier arrangement is chosen.

3.6. Resource-use efficiency

Published quantitative results on the resource implications of closed multi-tier cultivation are consolidated in Table 4.

Table 4.

Resource-use indicators of closed (hydroponic) versus conventional cultivation

Indicator	Closed hydroponic system	Conventional cultivation	Ratio
Yield, $kg \cdot m^{-2} \cdot year^{-1}$	41 ± 6.1	3.9 ± 0.21	11 ± 1.7 times higher
Water use, $L \cdot kg^{-1} \cdot year^{-1}$	20 ± 3.8	250 ± 25	≈ 13 times lower
Energy use, $kJ \cdot kg^{-1} \cdot year^{-1}$	90 000 ± 11 000	1 100 ± 75	82 ± 11 times higher
Electrical productivity, $kg \cdot (kW \cdot h)^{-1}$	0.11-0.14	-	governed by lighting

The values are drawn from Barbosa et al. and Kozai [6, 12]. They record the dual nature of closed multi-tier systems in numerical form: an advantage exceeding one order of magnitude in yield, and approaching one order of magnitude in water use, is paid for by a deficit approaching two orders of magnitude in energy. The electrical-productivity range of 0.11-0.14 $kg \cdot (kW \cdot h)^{-1}$ further indicates that the photon efficacy of the lighting system, rather than any other subsystem, is the quantity that governs this indicator [24].

3.7. Effect of constructive parameters on technological indicators

In designing a multi-tier unit, the number of tiers and the spacing between them are the decisive parameters. Increasing the number of tiers raises Kf in expression (2) but produces five adverse consequences: the volumetric heat load rises, because a luminaire is installed at every tier and a substantial share of its power becomes heat; the air temperature increases towards the upper tiers, because the air stream absorbs additional heat at each tier in sequence; reducing the inter-tier spacing disturbs the airflow above the canopy and slows gas exchange; reducing the luminaire-to-canopy distance increases the horizontal non-uniformity of illumination; and access to the upper tiers for servicing becomes more difficult. These opposed effects are consolidated in Table 5.

Table 5.

Effect of constructive parameters on technological indicators

Parameter	Effect of an increase - positive	Effect of an increase - negative	Recommended value
Number of tiers	yield per unit floor area rises	heat load and non-uniformity rise	3-4 (small-volume unit)
Inter-tier spacing	airflow above the canopy improves	overall height of the unit rises	350-450 mm
Air flow rate	non-uniformity decreases	fan energy consumption rises	determined by calculation
Lighting power	photosynthesis intensifies	heat load and energy use rise	determined from PPFD
Substrate volume	irrigation interval lengthens	mass and overall dimensions rise	4-6 L per container

Every parameter in Table 5 acts in both directions simultaneously; none produces monotonic improvement. This is the formal reason why the design of a multi-tier unit must be posed as a constrained multi-criteria problem rather than as the optimisation of a single objective. Within this framework the inter-tier temperature difference of expression (4) is treated as a constraint: to secure uniform crop development it is considered appropriate that ΔT should not exceed 2 °C, while the favourable range of air velocity above the canopy is 0.3-1.0 $m \cdot s^{-1}$.

Overall dimensions are constrained by the conditions of domestic use: the width follows from the door opening of the room and the depth from the requirement that the user can reach the plants. In the reviewed unit these requirements are met by 1200 mm width and 500 mm depth, while the height of 2400 mm accommodates three tiers in accordance with expression (3).

3.8. Coverage matrix of the normative base

The assessment of current normative documents against the eight criteria is presented in Table 6.

Table 6.

Coverage matrix of normative documents (K1 - structural design and loads; K2 - air-exchange calculation; K3 - photosynthetic radiation quantities; K4 - inter-tier ΔT; K5 - air velocity above the canopy; K6 - illumination non-uniformity; K7 - irrigation hardware; K8 - applicability to small-volume multi-tier constructions)

Level	Document	K1	K2	K3	K4	K5	K6	K7	K8
National	ShNQ 2.09.08-21. Greenhouses and hotbeds	+	±	–	–	–	–	–	–
National	ShNQ 2.01.05-24. Natural and artificial lighting	–	–	–	–	–	±	–	–
National	ShNQ 2.04.05-22.	–	+	–	–	±	–	–	–

	Heating, ventilation and air conditioning								
CIS	SP 107.13330.2012. Greenhouses and hotbeds	+	–	–	–	–	–	–	–
CIS	RD-APK 1.10.09.01-14 (technological design norms)	±	+	±	–	–	–	±	–
CIS	GOST R 57671-2017 (LED luminaires for greenhouses)	–	–	+	–	–	±	–	–
CIS	GOST R 58461-2019 (plant lighting - terms)	–	–	±	–	–	–	–	–
International	EN 13031-1:2019. Greenhouses - design and construction	+	–	–	–	–	–	–	–
International	ANSI/ASABE S640, S642	–	–	+	–	–	–	–	–
International	ANSI/ASAE EP406.4	–	+	–	–	±	–	–	–
International	ISO 9261, ISO 9912-2	–	–	–	–	–	–	+	–
Coverage index Ik, %	M = 11	27.3	27.3	18.2	0	0	0	9.1	0
Partial coverage Ik±, %	M = 11	36.4	36.4	36.4	0	18.2	18.2	18.2	0

Three findings follow. First, the classical engineering criteria - structural design and loads (Ik = 27.3 %) and air-exchange calculation (Ik = 27.3 %) - are comparatively well covered, but exclusively for industrial-scale facilities. Second, photosynthetic radiation quantities reach a coverage of 18.2 %, and this coverage is generated entirely by international and intergovernmental standards [27], while the national lighting code still specifies illuminance in lux, on a scale weighted to human vision. Third, and most importantly, four criteria - K4 (inter-tier temperature difference), K5 (air velocity above the canopy), K6 (illumination non-uniformity) and K8 (applicability to small-volume multi-tier constructions) - return a full coverage index of exactly 0 %. For K5 and K6 the partial index reaches 18.2 %, but that partial coverage is indirect, being derived from requirements written for a different object: residential and public buildings, or industrial greenhouses.

The result for K8 deserves separate emphasis: across all eleven documents the index is 0 %. Not one of them names a multi-tier, sole-source-lighting facility of less than 100 m² as a design object. What the documents do regulate - minimum facility area, load-bearing capacity, snow and wind loads - is precisely what is irrelevant for a building-integrated unit of a few square metres.

3.9. Indicators proposed for a sectoral normative document

To close the gaps identified by the coverage matrix, a set of indicators applicable to small-volume multi-tier units was compiled (Table 7).

Table 7.

Verifiable indicators proposed for small-volume multi-tier cultivation units

Indicator	Symbol	Proposed value	Basis
Inter-tier temperature difference	ΔT	< 2 °C	condition of uniform crop development
Air velocity above the canopy	v	0.3-1.0 $m \cdot s^{-1}$	leaf boundary-layer resistance
Photosynthetic photon flux density	PPFD	150-250 $\mu mol \cdot m^{-2} \cdot s^{-1}$	recommended range for leafy crops
Daily light integral	DLI	12-17 $mol \cdot m^{-2} \cdot day^{-1}$	expression (6) with τf = 16-18 h
Illumination non-uniformity	δ	< 20 %	condition of uniform yield across a tier
Number of tiers	n	3-4	favourable range from Table 5
Inter-tier spacing	hy	350-450 mm	expression (3)
Substrate volume	Vs	4-6 L per container	irrigation-interval requirement

All eight indicators are verifiable, that is, directly measurable with standard instrumentation. They can be introduced without altering the structure of existing documents, either as a dedicated section of the national greenhouse code [30] or as a stand-alone sectoral norm.

4. Discussion

4.1. Interpretation of the identified normative gaps

The coverage matrix shows that the gap is systematic rather than accidental. All eleven documents are built on a shared underlying logic: they treat the facility primarily as a *building*, and they regulate its resistance to external environmental actions - snow, wind, external temperature difference. For free-standing, large-area, naturally lit structures this logic is entirely appropriate, and it is the reason why EN 13031-1 and SP 107.13330 achieve high internal consistency within their own scope [26, 29]. For a small-volume, building-integrated, sole-source-lighting unit, however, external climatic action is effectively absent: the envelope retains an internal heat load, and the governing structural case is a permanent gravity load of 30-50 kg per tier. The 27.3 % coverage of criterion K1 therefore does not transfer to the review object; it is coverage that exists formally but does not apply substantively.

The situation with criterion K3 illustrates a different failure mode - a metrological one. International practice evaluates radiation incident on plants through the photon flux density in the 400-700 nm band, in accordance with ANSI/ASABE S640 [27], and the CIS standards for LED horticultural luminaires have adopted the same approach. The national lighting code, by contrast, still specifies illuminance in lux. Because the lux is weighted by the photopic sensitivity of the human eye, which peaks near 555 nm, the spectrum of a horticultural LED with maxima in the blue (≈ 450 nm) and red (≈ 660 nm) regions is systematically under-read on that scale. This is not merely an inconvenience of units: a lighting regime judged "sufficient" in lux may deliver a PPFD several times below the physiologically required value, so the metrological mismatch propagates directly into design error. Since the relationship between PPFD, photoperiod and crop response has been quantified for leafy crops in a number of independent studies [10, 23], the corrective measure is available and requires only that the correct quantity be adopted.

The most consequential result is the complete absence of coverage for K4, K5, K6 and K8. These are precisely the quantities that come into existence *because* the construction is multi-tier and that are meaningless in a single-tier structure: in a conventional greenhouse the notion of an "inter-tier temperature difference" does not arise. The normative base therefore fails to recognise an entire class of physical phenomena introduced by vertical stacking. The general air-exchange procedures available in the national HVAC code and in ANSI/ASAE EP406.4 [28] both assume a well-mixed control volume, and neither accounts for air travelling sequentially past a series of heat-emitting tiers - the mechanism that generates the gradient of expression (4) in the first place.

4.2. Comparison with the international literature

Resource use. The ratios consolidated in Table 4 are corroborated, in direction if not in magnitude, by independent studies. Graamans et al. compared a plant factory and a greenhouse under a single methodology and found that water-use efficiency in the closed system is dramatically higher while energy use is 2-5 times greater depending on climate zone [7]; Zhang and Kacira reached a comparable conclusion for energy-use efficiency [14]. These factors are far smaller than the 82 ± 11 ratio of Table 4, yet there is no contradiction: Graamans and Zhang used a greenhouse as the comparison base, whereas Table 4 compares against open-field conventional cultivation. The difference in baseline shifts the result by more than an order of magnitude, which is itself a methodological finding of this review - resource-efficiency figures for vertical systems are meaningless unless the comparison baseline is stated explicitly, and the frequent citation of such ratios without that qualification is a recurring source of confusion in the applied literature.

Touliatos et al. confirmed experimentally that vertical arrangement increases lettuce yield per unit area relative to conventional horizontal hydroponics, while simultaneously reporting that light and temperature conditions differ between the upper and lower tiers and that this difference affects crop quality [13]. That observation supports the central argument developed here: raising n increases Kf in expression (2) but also increases ΔT in expression (4), so floor-area productivity and product uniformity are competing rather than complementary objectives. In an industrial facility the conflict can be resolved by investment in air handling; in a small-volume unit it must be resolved by control.

Microclimate uniformity. Zhang, Kacira and An compared four air-distribution duct configurations in a multi-tier system numerically and found that the best configuration gave a mean air velocity of 0.42 $m \cdot s^{-1}$ with a coefficient of variation of 44 %, with only 64 % of measurement points falling within the target range of 0.3-1.0 $m \cdot s^{-1}$; the remaining configurations reached coefficients of variation of 45-51 % [15]. This is a strong result for the present argument. Even in an industrial system equipped with purpose-designed distribution ducting, CV computed by expression (5) does not fall below about 40 %, and more than a third of the canopy lies outside the target velocity window. The implication is that the uniformity problem cannot be eliminated by constructive means alone and that compensation at the level of the control algorithm is required. Subsequent CFD analyses of climate uniformity in indoor plant factories have reinforced this conclusion [16], and a recent review of CFD applications to indoor vertical farm microclimate reports that non-uniformity remains the dominant unresolved issue across the published body of work [20].

Chen et al. developed an experimentally validated CFD model for a micro plant factory and, in the optimised configuration, reduced the relative standard deviation of air velocity to 18.34 % and that of relative humidity to 2.05 % [18]. In terms of overall dimensions this is the closest published analogue to the review object, and its result is important in two respects. First, it demonstrates that a CV below 20 % is attainable in a small-volume unit, so the corresponding requirement is not utopian. Second, it lies in the same numerical range as the $\delta < 20$ % illumination-uniformity limit proposed in Table 7, which indirectly supports the internal consistency of the proposed indicator set.

Sohn et al. examined airflow uniformity in a shipping-container vertical farm and showed that the standard configuration produces marked non-uniformity between tiers [17]. Lee et al. demonstrated that environmental uniformity in a seedling plant factory can be improved by porous panels [19]; that solution is inexpensive, but it introduces additional hydraulic resistance and therefore demands greater fan power - an independent confirmation of the trade-off recorded in the "air flow rate" row of Table 5. Bournet and Boulard, reviewing the effect of ventilator configuration on distributed greenhouse climate, reached the analogous conclusion one facility generation earlier [22], which suggests that the uniformity problem is not specific to vertical farming but is inherited and intensified by it.

Physiological limits on air velocity. Kitaya et al. studied the effect of air current speed on gas exchange in leaves and canopies and showed that boundary-layer resistance at the leaf surface depends on air velocity and directly governs the rates of photosynthesis and transpiration [21]. At very low velocities the boundary layer thickens and CO_2 diffusion into the leaf is impeded; at excessive velocities the plants experience mechanical stress and water consumption rises. This two-sided constraint provides the physiological rationale for the 0.3-1.0 $m \cdot s^{-1}$ range proposed in Table 7 and allows it to be interpreted as a permissible zone around an optimum, rather than as an arbitrarily selected interval.

Energy. Van Delden et al. identify high energy consumption, and the production cost associated with it, as the principal barrier to large-scale implementation of vertical farming [9]. Avgoustaki and Xydis proposed shifting the lighting schedule to hours of low electricity tariff as one route to reducing energy cost [11]. This option is particularly attractive for small-volume and domestic units, whose production schedules are not rigid. However, expression (6) shows that DLI is the product of PPFD and photoperiod, so temporal shifting must preserve DLI: shortening the photoperiod requires a proportional increase in PPFD, which, by Table 5, raises the instantaneous heat load and thus the very quantity that the fan-only microclimate system of a small unit is least able to remove. Tariff-driven optimisation therefore cannot be treated as an isolated scheduling problem; it is coupled to the thermal design. Photon efficacy of the fixture is the other lever, and it acts directly on the electrical-productivity figure of 0.11-0.14 $kg \cdot (kW \cdot h)^{-1}$ reported in Table 4 [24].

4.3. Why small-volume multi-tier units are an under-researched niche

The analysis suggests four reinforcing reasons for the scarcity of research on this class.

Economic asymmetry. Research funding in controlled-environment agriculture is largely channelled through industrial-scale projects, where a one-percent energy saving yields a large absolute return. In a domestic unit the absolute return is small and does not repay the cost of a rigorous study, even though the relative inefficiency is greater.

Commercial opacity. Small multi-tier units exist on the market, but they are engineered as products rather than as research objects. Manufacturers do not publish constructive parameters, air flow rates or energy balances, and no independently verified data set has therefore accumulated. The absence of data is then read as an absence of problems.

The scaling fallacy. A small unit is commonly regarded as a scaled-down industrial system. Microclimate processes, however, do not scale linearly. As the enclosed volume decreases, the volumetric heat load ($W \cdot m^{-3}$) rises because luminaire density per unit volume is preserved while the surface available for heat removal contracts; the circulation path shortens; and the vertical gradient accumulates between closely spaced tiers instead of being dispersed. The migration of the dominant constraint recorded in Table 3 - from energy consumption to control quality - is the observable signature of this non-linearity.

Absence of normative incentive. The K8 = 0 % result closes a feedback loop: because no document names the class as a design object, no compliance testing is required; because no testing is required, no research is commissioned; and because no research exists, no document can be drafted. Only an independent scientific initiative can break this loop, and the indicator set of Table 7 is intended precisely as the entry point.

4.4. Practical implications

Three practical implications follow. First, for the design of small multi-tier units the governing design case is not the maximum attainable temperature but the *uniformity* of temperature along the tiers: expression (4) rather than an absolute limit should be treated as the binding constraint, since a unit that satisfies a maximum-temperature specification may still deliver a non-uniform crop. Second, envelope selection in sole-source-lighting units should be made on insulation and internal reflectance criteria alone, which permits triple-wall polycarbonate at 2.2-2.5 $W \cdot m^{-2} \cdot K^{-1}$ to be adopted without the light-transmittance penalty that would disqualify it in a naturally lit structure. Third, the indicator set of Table 7 is formulated so that each entry is measurable with instrumentation already prescribed by existing metrology standards, which means adoption requires no new measurement infrastructure - an important consideration for national standardisation bodies.

More broadly, the transition of controlled-environment agriculture towards plant factories and urban production has been described as a continuing trajectory [25], and the maturation of that trajectory now depends less on new hardware concepts than on closing the specification gap for the small end of the size range, where the number of installed units is largest and the engineering support is weakest.

4.5. Limitations

Five limitations qualify the results.

First, the study is a critical-analytical review. No new experiments were conducted and no new numerical values were generated; every quantitative indicator belongs to the cited sources. The ratios in Table 4 were obtained for particular crops, climate zones and lighting systems and cannot be transferred directly to other conditions.

Second, the coverage matrix is bounded by the eleven documents analysed. A change in M alters the absolute values returned by expression (7), but it does not alter the relation between criteria - in particular the zero coverage of K4, K5, K6 and K8 - because that zero follows from the subject matter of the documents rather than from their number. Adding further documents of the same generation would lower the percentages for K1-K3 without introducing any coverage of K4-K6.

Third, the "+", "±" and "–" ratings are qualitative and involve expert judgement. Although the assignment rule was fixed in advance - a numerical value or a verifiable requirement is needed for "+" - subjectivity cannot be entirely excluded in borderline cases assigned to "±".

Fourth, normative documents are periodically revised. The analysis reflects the state as of 2025 and should be repeated as new editions are issued.

Fifth, a single constructive scheme was taken as the anchor: a three-tier unit with bottom air admission and lateral supply and exhaust ducts. Results may differ for alternative aeration schemes, such as independent air supply to each tier or cross-flow ventilation, and the generality of the recommended ranges in Table 5 beyond the analysed scheme has not been established.

4.6. Requirements for further work

The review imposes a specific agenda on subsequent stages. A tier-resolved heat-balance model is required that reproduces the sequential temperature rise along the air path and links air flow rate as an input to ΔT of expression (4) as an output; a well-mixed single-volume model is by construction incapable of this. The minimum air flow rate that satisfies ΔT < 2 °C must then be derived theoretically and the fan operating point determined by intersecting the fan characteristic with the network characteristic. The lighting regime must be justified through DLI of expression (6) jointly with the microclimate constraints, since lighting power is simultaneously the source of photosynthesis and the dominant heat load - a coupling that is not captured when lighting and climate are designed separately, as is common practice [5]. Microclimate uniformity must be measured through CV of expression (5) and validated experimentally against the CFD-derived benchmarks discussed above [16, 18]. Finally, the resulting values should be formalised as an indicator set in the form of Table 7 and submitted as the basis for a sectoral normative document.

5. Conclusions

1. Four stages in the development of protected-ground engineering were distinguished, and a consistent pattern was established: with each transition the number of controlled factors and the specific energy consumption per unit of product increased together. This defines the central design contradiction of the field - an improvement in control quality must not be paid for by an increase in energy consumption.

2. The classification of protected-ground facilities by nine independent attributes was formalised as a vector, and the review object was located within the classification space as a rack-type, combined-covering, sole-source-lighting, small-volume-substrate, fully automated, small-volume (< 100 m^2), building-integrated unit. The intersection of these seven attribute values constitutes the least studied class in the international literature.

3. Comparison of covering materials showed that a reduction of light transmittance from 88-90 % to 70-75 % (a factor of 1.2) is accompanied by a reduction of the heat transfer coefficient from 5.8-6.0 to 2.2-2.5 $W \cdot m^{-2} \cdot K^{-1}$ (a factor of 2.4). In sole-source-lighting units the conflict between these properties disappears, and the material is selected unambiguously on the insulation criterion, with internal reflectance becoming the secondary design variable.

4. Closed multi-tier systems raise yield by 11 ± 1.7 times (41 ± 6.1 against 3.9 ± 0.21 $kg \cdot m^{-2} \cdot year^{-1}$) and reduce water use approximately 13-fold (20 ± 3.8 against 250 ± 25 $L \cdot kg^{-1}$), but consume 82 ± 11 times more energy (90 000 ± 11 000 against 1 100 ± 75 $kJ \cdot kg^{-1}$), with electrical productivity of 0.11-0.14 $kg \cdot (kW \cdot h)^{-1}$. The magnitude of these ratios is baseline-dependent and must always be reported together with the comparison base.

5. Recommended ranges of constructive parameters for a small-volume unit were established: 3-4 tiers, inter-tier spacing 350-450 mm, substrate volume 4-6 L per container, design load 30-50 kg per tier, air velocity above the canopy 0.3-1.0 $m \cdot s^{-1}$ and inter-tier temperature difference not exceeding 2 °C. Every parameter acts in two opposing directions, so the design task is inherently a constrained multi-criteria problem.

6. Coverage analysis of eleven normative documents against eight criteria returned coverage indices of 27.3 % for structural design and for air-exchange calculation, 18.2 % for photosynthetic radiation quantities and 9.1 % for irrigation hardware, while the indices for inter-tier temperature difference, air velocity above the canopy, illumination non-uniformity and applicability to small-volume multi-tier constructions were all exactly 0 %.

7. Eight verifiable indicators were proposed for inclusion in a sectoral normative document: ΔT < 2 °C; air velocity 0.3-1.0 $m \cdot s^{-1}$; PPFD 150-250 $\mu mol \cdot m^{-2} \cdot s^{-1}$; DLI 12-17 $mol \cdot m^{-2} \cdot day^{-1}$; illumination non-uniformity below 20 %; 3-4 tiers; inter-tier spacing 350-450 mm; and substrate volume 4-6 L per container. All are measurable with instrumentation prescribed by existing metrology standards, so their adoption requires no new measurement infrastructure.

Author Contributions

The author solely conceived the study, designed the review protocol and the coverage-analysis methodology, collected and analysed the sources, prepared the tables and wrote the manuscript.

Funding

This research received no external funding.

Conflicts of Interest

The author declares no conflict of interest.

References

1. Hanan, J.J. Greenhouses: Advanced Technology for Protected Horticulture; CRC Press: Boca Raton, FL, USA, 1998; 708 p. ISBN 978-0-8493-1698-2.

2. Stanghellini, C.; Van 't Ooster, B.; Heuvelink, E. Greenhouse Horticulture: Technology for Optimal Crop Production; Wageningen Academic Publishers: Wageningen, The Netherlands, 2019; 300 p. DOI: 10.3920/978-90-8686-879-7.

3. Despommier, D. The Vertical Farm: Feeding the World in the 21st Century; Thomas Dunne Books: New York, NY, USA, 2010. ISBN 978-0-312-61139-2.

4. Kozai, T.; Niu, G.; Takagaki, M. (Eds.) Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production, 2nd ed.; Academic Press/Elsevier: London, UK, 2019. ISBN 978-0-12-816691-8.

5. Kozai, T. (Ed.) Smart Plant Factory: The Next Generation Indoor Vertical Farms; Springer: Singapore, 2018. DOI: 10.1007/978-981-13-1065-2.

6. Kozai, T. Resource use efficiency of closed plant production system with artificial light. Proc. Jpn. Acad. Ser. B 2013, 89, 447–461. DOI: 10.2183/pjab.89.447.

7. Graamans, L.; Baeza, E.; van den Dobbelsteen, A.; Tsafaras, I.; Stanghellini, C. Plant factories versus greenhouses: Comparison of resource use efficiency. Agric. Syst. 2018, 160, 31–43. DOI: 10.1016/j.agsy.2017.11.003.

8. Graamans, L.; Tenpierik, M.; van den Dobbelsteen, A.; Stanghellini, C. Plant factories: Reducing energy demand at high internal heat loads through façade design. Appl. Energy 2020, 262, 114544. DOI: 10.1016/j.apenergy.2020.114544.

9. van Delden, S.H.; SharathKumar, M.; Butturini, M.; Graamans, L.J.A.; Heuvelink, E.; Kacira, M.; Kaiser, E.; Klamer, R.S.; Klerkx, L.; Kootstra, G.; et al. Current status and future challenges in implementing and upscaling vertical farming systems. Nat. Food 2021, 2, 944–956. DOI: 10.1038/s43016-021-00402-w.

10. Kelly, N.; Choe, D.; Meng, Q.; Runkle, E.S. Promotion of lettuce growth under an increasing daily light integral depends on the combination of the photosynthetic photon flux density and photoperiod. Sci. Hortic. 2020, 272, 109565. DOI: 10.1016/j.scienta.2020.109565.

11. Avgoustaki, D.D.; Xydis, G. Energy cost reduction by shifting electricity demand in indoor vertical farms with artificial lighting. Biosyst. Eng. 2021, 211, 219–229. DOI: 10.1016/j.biosystemseng.2021.09.006.

12. Barbosa, G.L.; Gadelha, F.D.A.; Kublik, N.; Proctor, A.; Reichelm, L.; Weissinger, E.; Wohlleb, G.M.; Halden, R.U. Comparison of land, water, and energy requirements of lettuce grown using hydroponic vs. conventional agricultural methods. Int. J. Environ. Res. Public Health 2015, 12, 6879–6891. DOI: 10.3390/ijerph120606879.

13. Touliatos, D.; Dodd, I.C.; McAinsh, M. Vertical farming increases lettuce yield per unit area compared to conventional horizontal hydroponics. Food Energy Secur. 2016, 5, 184–191. DOI: 10.1002/fes3.83.

14. Zhang, Y.; Kacira, M. Comparison of energy use efficiency of greenhouse and indoor plant factory system. Eur. J. Hortic. Sci. 2020, 85, 310–320. DOI: 10.17660/eJHS.2020/85.5.2.
15. Zhang, Y.; Kacira, M.; An, L. A CFD study on improving air flow uniformity in indoor plant factory system. Biosyst. Eng. 2016, 147, 193–205. DOI: 10.1016/j.biosystemseng.2016.04.012.
16. Zhang, Y.; Kacira, M. Analysis of climate uniformity in indoor plant factory system with computational fluid dynamics (CFD). Biosyst. Eng. 2022, 220, 73–86. DOI: 10.1016/j.biosystemseng.2022.05.009.
17. Sohn, J.; Liulys, M.; Avgoustaki, D.D.; Xydis, G. CFD analysis of airflow uniformity in a shipping-container vertical farm. Comput. Electron. Agric. 2023, 215, 108363. DOI: 10.1016/j.compag.2023.108363.
18. Chen, X.; Hou, T.; Liu, S.; Wang, J.; Zhang, H.; Li, Y. Design of a micro-plant factory using a validated CFD model. Agriculture 2024, 14, 2227. DOI: 10.3390/agriculture14122227.
19. Lee, S.-W.; Seo, I.-H.; An, S.-W.; Na, H.-Y. Improvement of environmental uniformity in a seedling plant factory with porous panels using computational fluid dynamics. Horticulturae 2023, 9, 1027. DOI: 10.3390/horticulturae9091027.
20. Sarailoo, H.; Campbell, L.; Bougherara, H. A comprehensive review on the application of computational fluid dynamics in enhancing indoor vertical farm microclimate. J. Biosyst. Eng. 2025, 50, 145–169. DOI: 10.1007/s42853-025-00257-0.
21. Kitaya, Y.; Tsuruyama, J.; Shibuya, T.; Yoshida, M.; Kiyota, M. Effects of air current speed on gas exchange in plant leaves and plant canopies. Adv. Space Res. 2003, 31, 177–182. DOI: 10.1016/S0273-1177(02)00747-0.
22. Bournet, P.-E.; Boulard, T. Effect of ventilator configuration on the distributed climate of greenhouses: A review of experimental and CFD studies. Comput. Electron. Agric. 2010, 74, 195–217. DOI: 10.1016/j.compag.2010.08.007.
23. Pennisi, G.; Pistillo, A.; Orsini, F.; Cellini, A.; Spinelli, F.; Nicola, S.; Fernandez, J.A.; Crepaldi, A.; Gianquinto, G.; Marcelis, L.F.M. Optimal light intensity for sustainable water and energy use in indoor cultivation of lettuce and basil under red and blue LEDs. Sci. Hortic. 2020, 272, 109508. DOI: 10.1016/j.scienta.2020.109508.
24. Kusuma, P.; Pattison, P.M.; Bugbee, B. From physics to fixtures to food: Current and potential LED efficacy. Hortic. Res. 2020, 7, 56. DOI: 10.1038/s41438-020-0283-7.
25. Shamshiri, R.R.; Kalantari, F.; Ting, K.C.; Thorp, K.R.; Hameed, I.A.; Weltzien, C.; Ahmad, D.; Shad, Z.M. Advances in greenhouse automation and controlled environment agriculture: A transition to plant factories and urban agriculture. Int. J. Agric. Biol. Eng. 2018, 11, 1–22. DOI: 10.25165/j.ijabe.20181101.3210.
26. EN 13031-1:2019. Greenhouses — Design and Construction — Part 1: Commercial Production Greenhouses; CEN: Brussels, Belgium, 2019.
27. ANSI/ASABE S640 JUL2017 (R2022). Quantities and Units of Electromagnetic Radiation for Plants (Photosynthetic Organisms); ASABE: St. Joseph, MI, USA, 2022.
28. ANSI/ASAE EP406.4 JAN2003 (R2008). Heating, Ventilating and Cooling Greenhouses; ASAE: St. Joseph, MI, USA, 2008.
29. SP 107.13330.2012. Greenhouses and Hotbeds. Revised Edition of SNiP 2.10.04-85; Ministry of Construction of the Russian Federation: Moscow, Russia, 2012. (In Russian)
30. ShNQ 2.09.08-21. Greenhouses and Hotbeds; Ministry of Construction and Housing and Communal Services of the Republic of Uzbekistan: Tashkent, Uzbekistan, 2024. (In Uzbek). Available online: https://lex.uz/docs/-7107247