SYSTEMATIC ANALYSIS OF MULTI-TIER CULTIVATION UNIT DESIGNS AND THE NORMATIVE BASE FOR PROTECTED CULTIVATION

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Abstract: Purpose. To systematically analyse the design solutions of multi-tier cultivation units for protected cultivation, their technological and resource indicators, and the applicable normative framework; to formulate a classification system for small-volume multi-tier units and to quantify gaps in the normative base. Methods. A critical-analytical review was performed. The source base included international scientific publications, dissertations from the CIS scientific school, legislation and urban-planning standards of the Republic of Uzbekistan, and EN, ISO and ANSI/ASABE standards. Facilities were classified by nine independent attributes expressed in vector form; constructions were compared across nine indicators; eleven normative documents were assessed against eight criteria on a three-level scale, and a coverage index was calculated for each criterion. Results. Four stages of protected-cultivation engineering development were distinguished, revealing a consistent pattern: the number of controlled factors and the specific energy consumption per unit of product increase together. Coverage analysis showed a 0% coverage index for four criteria: inter-tier temperature difference, air velocity above the plant canopy, illumination non-uniformity, and applicability to small-volume multi-tier constructions. Conclusions. A small-volume, three-tier, fully automated unit using only artificial lighting occupies the least studied intersection of the classification space.

Keywords: protected cultivation, multi-tier unit, mini-greenhouse, plant factory, classification, microclimate uniformity, temperature gradient, air exchange, PPFD, DLI, normative base, coverage index, energy efficiency

1. Introduction

Protected-cultivation structures are engineering systems that protect plants from adverse external influences and create an artificial microclimate for them. Their engineering function is to maintain the temperature, air and substrate humidity, photosynthetically active radiation, and carbon dioxide concentration required by plants within specified limits throughout the growing period. J.J.Hanan describes this function from an engineering perspective as a greenhouse environment in which human-controlled factors are given priority over natural factors [16]. According to this definition, the development of protected-cultivation engineering can be viewed as a process in which the share of natural factors decreases while the share of controlled factors increases.

In regions where land resources are limited, irrigation-water scarcity is intensifying, and urbanization is proceeding rapidly, multi-tier (vertical) cultivation systems are regarded as one of the most promising directions. The conceptual foundations of these systems were formulated by D.Despommier, who substantiated food production within cities and multi-storey buildings as a technically feasible and increasingly inevitable direction under population growth [18]. The field was subsequently developed from an engineering perspective by T. Kozai and his school, and plant factories with artificial lighting (PFAL) emerged as an independent class of cultivation technology [17, 21].

Four conditional stages can be distinguished in the development of protected-cultivation engineering, and their sequence reveals an important regularity: at each successive stage, the number of controlled factors increased, while specific energy consumption per unit of product also increased. This regularity defines the principal contradiction of the field: improving the quality of control should not be accompanied by an increase in energy consumption. The contradiction is particularly acute for small-volume units because centralized air-handling systems, heat recovery, and large thermal-storage systems are economically unjustified in such installations.

The development of protected cultivation in the Republic of Uzbekistan is supported at the level of state policy. Decisions have been adopted to create additional conditions for the development of greenhouse complexes [4] and to improve the efficiency of greenhouse enterprises [5]; a mechanism has been established for partial state compensation of the costs of introducing water-saving irrigation technologies in agriculture [6]; procedures have been approved for accelerating the introduction of renewable-energy sources and energy-saving technologies [7]; and general energy-efficiency requirements are regulated by a special law [8]. These documents directly confirm the relevance of the research topic. However, they are primarily oriented toward industrial-scale greenhouse enterprises, leaving small-volume and household units outside their scope.

The literature analysis shows that existing scientific results are distributed between two poles. On the one hand, extensive research has accumulated on industrial-scale plant factories: resource-use efficiency [19, 21], climate uniformity [26], reduction of energy demand through envelope design [20], and temporal shifting of energy costs [23]. On the other hand, units designed for household and small-volume conditions are usually developed as commercial products rather than scientific objects; their design and technological parameters, energy consumption, and water-use indicators are generally not published or independently verified. Consequently, dimensional reduction is often achieved by simply scaling down solutions tested in industrial systems, although microclimate processes are not linearly related to scale.

A strong scientific school in protected-cultivation engineering has developed in the CIS countries. It has substantiated the structure of machinery complexes and parameters of working bodies, energy-saving lighting devices for multi-tier narrow-rack technologies, automatic nutrient-solution delivery in low-volume hydroponic greenhouses, adaptation of drip irrigation to winter greenhouse conditions, improvement of energy efficiency through optimal temperature control, and adaptive control methods. However, most of these studies concern industrial-scale structures and focus on improving one individual system - lighting, irrigation, or heating.

The integrated substantiation of design and technological parameters for a small-volume, three-tier unit in which all systems are combined into a single control loop has not been considered. Thus, the scientific gap can be formulated as follows: the smallest and least technically equipped segment of the multi-tier-unit class - small-volume, artificial-light-only, fully automated units—has not been systematically covered either in the scientific literature or in the normative base. The quantitative extent of this gap has not previously been assessed.

The purpose of this article is to systematically analyse the design solutions, resource and technological indicators, and existing normative base of multi-tier cultivation units for protected cultivation; to formulate a classification system and criteria for selecting design parameters for small-volume multi-tier units; and to quantitatively assess normative gaps.

The scientific novelty of the work is determined by three aspects. First, the classification of protected-cultivation structures according to nine independent attributes is formalized in vector form for the first time, and the "empty cells" occupied by small-volume automated multi-tier units in the classification space are identified. Second, contradictory relationships between design parameters and technological indicators are consolidated in a unified analytical table, and recommended value ranges for small-volume units are substantiated. Third, a methodology for quantitatively assessing normative documents through a coverage matrix and coverage index is proposed; it identifies gaps numerically and provides indicators recommended for inclusion in sectoral documents.

2. Materials and Methods

2.1. Research object

The research object comprised design schemes of multi-tier cultivation units used in protected cultivation and the set of normative documents regulating their design and operation. As the practical reference point for the analysis, a three-tier mini-greenhouse protected by utility-model patent No. FAP 2882 of the Republic of Uzbekistan was considered. Its dimensions are 1200 mm in width, 500 mm in depth, and 2400 mm in height. Air enters through the left-hand channel from below, moves upward through the tiers, and is discharged through the right-hand channel.

2.2. Source base and selection criteria

Four groups of documents were included in the source base: (a) international scientific publications - peer-reviewed articles and monographs on plant factories, vertical farms, climate uniformity, and resource efficiency; (b) dissertations and reference works from the CIS scientific school; (c) laws of the Republic of Uzbekistan, Presidential and Cabinet decisions, and urban-planning standards (ShNQ); and (d) interstate (SP, GOST, RD-APK) and international (EN, ISO, ANSI/ASABE) standards. Inclusion criteria for scientific sources were publication years 1995–2025, direct relevance to multi-tier closed systems, microclimate uniformity, lighting regimes, or resource consumption, and the presence of numerical values or a validated model. For normative documents, the inclusion criterion was the presence of requirements or calculation methods related to protected-cultivation structures, their microclimate, lighting, or irrigation systems.

2.3. Classification methodology

Nine independent attributes were adopted for classifying protected-cultivation structures, and the position of a structure in 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 structure; k2 is the construction type; k3 is the envelope material; k4 is the heating method; k5 is the light source; k6 is the cultivation technology; k7 is the degree of automation; k8 is the usable area; and k9 is the location. The sets of types for each attribute form mutually non-overlapping classes, so any structure is represented by a unique point in the classification space. This formalization makes it possible to distinguish intersections covered and not covered in the literature.

2.4. Comparison indicators

A unified set of nine indicators was used to compare constructions: useful area, number of tiers, lighting type, microclimate-control method, irrigation scheme, level of control, personnel requirements, specific investment, and principal technological limitation. Envelope materials were compared by light transmittance, thermal transmittance coefficient, and service life.

The area-use efficiency of multi-tier placement was defined as:

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

where Kf is the area-use coefficient; n is the number of tiers; Ay is the useful area of one tier, m^2; and Ab is the floor area occupied by the unit, m^2.

The distance between tiers was calculated as the sum of three components:

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

where hy is the distance between tiers, mm; hyor is the height of the luminaire, mm; hz is the required clearance between the luminaire and plant top, mm; and hmax is the maximum plant height, mm.

Inter-tier temperature non-uniformity was defined as the difference between the air temperatures of the highest and lowest tiers:

$\Delta T = T_n - T_1$ (4)

where ΔT is temperature non-uniformity, °C; T_n is the air temperature of the highest (nth) tier, °C; and T_1 is the air temperature of the lowest tier, °C.

The coefficient-of-variation method was used to assess spatial uniformity of microclimate parameters:

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

where CV is the coefficient of variation, %; S is the standard deviation across measurement points; and $\bar{x}$ is the mean value of the parameter across all measurement points. This indicator makes it possible to bring results from different authors concerning air-velocity and humidity distributions onto a common scale.

The lighting regime was expressed not in lux, but through photosynthetic photon flux density and daily light integral:

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

where DLI is the daily light integral, mol/(m²·day); PPFD is photosynthetic photon flux density, μmol/(m²·s); and τf is the photoperiod duration, h. This approach is specified in ANSI/ASABE S640 [14]. Lux is unsuitable for evaluating plant lighting because it is weighted according to the spectral sensitivity of the human eye.

2.5. Methodology for normative-coverage analysis

Documents were divided into three levels: national (Uzbekistan), interstate (CIS), and international. A total of M = 11 documents (or groups of documents concerning one topic) were included. Each document was assessed against eight criteria: K1 - building structures and loads; K2 - air-exchange calculation methodology; K3 - photosynthetic lighting quantities (PPFD, DLI); K4 - permissible inter-tier temperature difference; K5 - air velocity above the plant canopy; K6 - illumination non-uniformity; K7 - requirements for irrigation equipment; K8 - direct applicability to small-volume (<100 m²) multi-tier constructions.

Assessment used a three-level scale: "+" means that the criterion is specified in the document by a numerical value or verifiable requirement; "±" means that the criterion is specified indirectly, generally, or for another object; "−" means that the criterion is not covered. The coverage index for each criterion was calculated as:

$I_k = (m_k / M) \cdot 100\%$ (7)

where I_k is the coverage index for criterion k, %; m_k is the number of documents covering the criterion at the "+" level; and M is the total number of documents included in the analysis. Partial coverage, $I_k\pm$, was calculated using the same expression while counting both "+" and "±" assessments.

2.6. Data processing

Numerical values from different sources were converted to common units: yield - kg/m² per year; water consumption - L/kg; energy consumption - kJ/kg; and electricity productivity - kg/(kWh). Reported standard deviations were retained in their original form. Because the study is a review, no new experiment was conducted and no new numerical values were introduced. All quantitative results belong to the cited sources, whereas the calculated coverage indices follow directly from the coverage matrix.

3. Results

3.1. Stages of protected-cultivation engineering development

The analysis identified four stages in the development of the field. During the first stage (late nineteenth century to the first half of the twentieth century), glass-covered structures operating under natural light and water heating were built. During the second stage (1960s–1980s), industrial-scale block greenhouse complexes and automatic ventilation and heating systems were introduced; this was also the period when the theoretical foundations of protected-cultivation engineering were established in the CIS countries [10, 11]. During the third stage (from the 1990s), low-volume substrate cultivation, drip irrigation, and computer-based climate control became widespread. In the fourth, current stage, natural light is completely eliminated in some systems and multi-tier, artificially lit plant factories are developing [17, 18].

Comparison of the stages reveals a regularity: as the number of controlled factors increases, specific energy consumption per unit of product also increases monotonically. This regularity forms the principal contradiction of the field: improving control quality should not increase energy consumption.

4.1. Interpretation of the identified gaps

The coverage-matrix results show that the gap in the normative base is systematic rather than accidental. All eleven documents are constructed according to the same logic: they primarily treat the structure as a construction object and regulate its resistance to external environmental effects such as snow, wind, and temperature differences. This logic is fully justified for freestanding, large-volume structures operating under natural light. In a small-volume, building-integrated, artificial-light-only unit, external climatic influence is almost absent: the envelope mainly contains internal heat loads, and the principal structural load is the mass of substrate and plants, within approximately 30…50 kg per tier. Therefore, the 27.3% coverage of K1 is not practically transferable to the research object - it is coverage that is "formally present but substantively inapplicable."

The situation identified for K3 deserves special attention. In international practice, radiation incident on plants is evaluated using photosynthetic photon flux density (PPFD) in the 400–700 nm range according to ANSI/ASABE S640 [14], and a similar approach has been adopted in CIS standards [12]. National standards still specify lighting using the lux scale intended for buildings [2]. Because lux is weighted according to human spectral sensitivity, with maximum sensitivity around 555 nm, the blue (450 nm) and red (660 nm) spectral peaks of LED grow lights are systematically undervalued when measured in lux. This is not merely a metrological mismatch - it is a source of design error because a lighting regime considered "sufficient" in lux may be several times below the required PPFD.

A general methodology for calculating air exchange is given in ShNQ 2.04.05-22 [3] and in international practice, particularly ANSI/ASAE EP406.4 [15]. However, both approaches treat the control volume as homogeneous and do not account for sequential air movement through tiers and the associated heat accumulation characteristic of multi-tier construction. The most important result is the complete absence of coverage for K4, K5, K6, and K8. These indicators are specific to multi-tier structures and have no meaning in a single-tier greenhouse: in a single-tier greenhouse, for example, the concept of an "inter-tier temperature difference" does not exist.

Thus, the normative base does not consider an entire class of new physical phenomena associated with multi-tier construction. This gap determines the practical significance of the present research results.

4.2. Comparison of results with the international literature

Resource consumption. The ratios summarized in Table 4 are supported by independent sources. L. Graamans and co-authors compared plant factories and greenhouses using the same methodology and showed that water-use efficiency in closed systems is substantially higher, while energy consumption is 2…5 times higher depending on the climate region [19]. Y. Zhang and M. Kacira reached similar conclusions [25]. These values are considerably smaller than the 82 ± 11-fold difference in Table 4, but there is no contradiction: Graamans compared a plant factory with a greenhouse, whereas Table 4 compares it with conventional open-field cultivation. The difference in comparison baselines determines the order of magnitude of the results and demonstrates the need to state the comparison baseline explicitly when reporting resource-efficiency indicators.

Experiments by D. Touliatos and co-authors confirmed that vertical placement substantially increases yield per unit area compared with conventional horizontal hydroponics; at the same time, the authors noted that differences in light and temperature conditions at upper tiers affect product quality [30]. This directly supports the principal thesis of the present analysis: increasing the number of tiers raises the Kf coefficient in Equation (2), but also increases ΔT in Equation (4), meaning that area-use efficiency and product uniformity are competing criteria.

Microclimate uniformity. Y. Zhang, M. Kacira, and L. An numerically compared four configurations of air-distribution ducts in a multi-tier system. In the best variant, mean air velocity was 0.42 m/s, the coefficient of variation was 44%, and only 64% of measurement points were within the target range of 0.3…1.0 m/s; in the other variants, the coefficient of variation reached 45…51% [26]. This is important because even in an industrial system equipped with centralized air-distribution ducts, the CV calculated according to Equation (5) does not fall below 40%. Therefore, the problem cannot be fully eliminated by structural solutions alone, and compensation at the control-algorithm level is required.

X. Chen and co-authors developed an experimentally validated CFD model for a micro-plant factory and achieved, in the optimized variant, a reduction in the relative standard deviation of air velocity to 18.34% and relative humidity to 2.05% [27]. This is the closest analogue to the research object in terms of dimensions, and its results are important in two respects. First, they demonstrate that achieving a CV below 20% in a small-volume unit is fundamentally possible. Second, the result is of the same order as the proposed $\delta < 20\%$ limit for illumination non-uniformity in Table 7, indirectly supporting the practical attainability of this limit.

J. Sohn and co-authors studied airflow uniformity in a container-type vertical farm and showed that substantial non-uniformity occurs between tiers in the standard configuration [28]. S.-W. Lee and co-authors substantiated the use of perforated panels to improve environmental uniformity [29]. Although this is an inexpensive solution, it creates additional hydraulic resistance and requires increased fan power, once again confirming the contradiction recorded in the “airflow rate” row of Table 5.

Physiological limits of air velocity. Y. Kitaya and co-authors studied the effect of airflow velocity on gas exchange of leaves and plant canopies and showed that boundary-layer resistance around leaves depends on airflow velocity and directly determines the intensity of photosynthesis and transpiration. When air velocity is too low, the boundary layer thickens and CO_2 entry into the leaf becomes more difficult; when velocity becomes excessive, plants are subjected to mechanical stress and water consumption increases. This dual constraint provides the physiological basis for the proposed 0.3…1.0 m/s range in Table 7 and allows it to be interpreted as an allowable zone around an optimum rather than an arbitrarily selected value.

Energy consumption. S.H. van Delden and co-authors identify high energy consumption and the associated production cost as a major barrier to large-scale implementation of vertical farming systems [22]. D.D. Avgoustaki and G. Xydis proposed shifting electricity demand to hours with lower electricity tariffs as one method of reducing energy costs [23]. This solution is particularly attractive for small-volume and household units because their production schedule is not rigid. However, Equation (6) shows that DLI is determined by the product of PPFD and photoperiod, meaning that shifting lighting in time should not alter DLI: shortening the photoperiod requires a proportional increase in PPFD, which, according to Table 5, increases the thermal load. Therefore, tariff optimization must be solved together with microclimate control.

4.3. Why small-volume multi-tier units are understudied

The analysis identifies four reasons for the limited study of this class. First, an economic reason: scientific research is commonly financed through industrial-scale projects, where a one-percent energy saving has a large absolute effect. In a household unit, the absolute effect is small and does not justify research expenditure. Second, commercial confidentiality: although small multi-tier units are available on the market, they are developed as products rather than scientific objects; manufacturers do not publish design parameters, airflow rates, or energy balances. Consequently, an independently verified database does not form.

Third, an incorrect assumption about scalability. A small unit is often regarded as a reduced-scale copy of an industrial system. In reality, microclimate processes are not linearly related to scale: as volume decreases, specific thermal load (W/m^3) increases, the air-circulation path becomes shorter, and the temperature gradient accumulates between tiers. The "main limitation" row in Table 3 records exactly this shift - the limitation moves from energy consumption toward control quality.

Fourth, the absence of normative incentives. The K8 = 0% condition shown in Table 6 creates a feedback loop: because there is no standard, research is not commissioned; because there is insufficient research, the standard is not developed. This cycle can only be broken by an independent scientific initiative.

4.4. National context and practical significance

In the Republic of Uzbekistan, dissertations defended under specialty 05.07.01 - "Agricultural and reclamation machinery. Mechanization of agricultural production processes" - have mainly concerned machines operating in open fields, including soil-processing aggregates, sowing and harvesting machinery, and cotton-picking equipment. Research on protected-cultivation structures and their automation within this specialty is practically absent. This confirms the novelty of the direction at the national level.

At the same time, national conditions are favorable for this direction: legal mechanisms have already been established to support greenhouse enterprises [4, 5], partially compensate the costs of water-saving technologies [6], and promote energy-saving technologies [7, 8]. Because small-volume multi-tier units have an approximately 13-fold advantage in water consumption, they are fully consistent with water-saving policy objectives. Their principal weakness - energy consumption - falls precisely within the scope of national energy-efficiency documents. Thus, the set of indicators proposed in Table 7 makes it possible to connect two policy directions in a single technical document.

4.5. Research limitations

The following limitations should be considered when interpreting the results. First, the study is a critical-analytical review; no new experiment was conducted and no new numerical values were obtained. All quantitative indicators belong to the cited sources. Therefore, the ratios in Table 4 were obtained for particular crop types, climatic regions, and lighting systems and cannot be transferred directly to other conditions.

Second, the coverage matrix is limited to the eleven documents included in the analysis. Changing M alters the absolute values of the indices calculated by Equation (7), but it does not change the relative pattern among criteria - particularly the zero coverage for K4, K5, K6, and K8 - because these zero results arise from the subject matter of the documents rather than merely from the number of documents.

Third, the “+”, “±”, and “–” assessments are qualitative. Although the criterion was strictly defined as the presence of a numerical value or verifiable requirement in the document, expert judgement cannot be completely excluded in borderline cases classified as “±”.

Fourth, normative documents are updated over time. The analysis reflects the situation as of 2025 and should be repeated when new editions are issued.

Fifth, one structural scheme - a three-tier unit with bottom air intake and left- and right-hand channels - was considered as the analytical object. Results may differ for other aeration schemes, such as independent air supply to each tier or cross-flow ventilation.

4.6. Requirements for future research

The results of the analysis impose the following requirements on subsequent research stages. First, a mathematical model of the heat balance across tiers should be developed, taking into account the sequential increase in temperature along the tiers; the model should link airflow rate as an input parameter to ΔT in Equation (4) as the output parameter. Second, the minimum airflow rate required to ensure $\Delta T < 2$ °C should be theoretically substantiated and determined by intersecting the required condition with the fan operating point and system characteristic. Third, the lighting regime should be substantiated using DLI according to Equation (6), linked with microclimate requirements, because lighting power is simultaneously a source of photosynthesis and the principal heat load. Fourth, microclimate uniformity should be measured using the CV indicator in Equation (5) and experimentally verified. Fifth, the resulting indicators should be formalized as a set corresponding to Table 7 and proposed for development of a sectoral normative document.

5. Conclusions

1. Four stages of protected-cultivation engineering development were distinguished, and a regularity was identified whereby the number of controlled factors and specific energy consumption per unit of product increase together. This regularity forms the principal contradiction of the field: improving control quality should not increase energy consumption.

2. The classification of protected-cultivation structures according to nine independent attributes was formalized in vector form, and the research object was placed as a precise point in the classification space: rack (tiered), combined envelope material, artificial lighting only, low-volume substrate, fully automated, small-volume (<100 m²), and building-integrated. The intersection of these seven characteristics constitutes the least studied class in the literature.

3. Comparative analysis of envelope materials showed that when light transmittance decreases from 88…90% to 70…75% (1.2-fold), the thermal transmittance coefficient decreases from 5.8…6.0 to 2.2…2.5 W/(m²·K) (2.4-fold). In artificially lit units, the conflict between these two requirements disappears and the material can be selected unambiguously according to thermal-insulation performance.

4. Closed multi-tier systems were found to increase yield by 11 ± 1.7 times (41 ± 6.1 kg/m² versus 3.9 ± 0.21 kg/m² for conventional cultivation) and reduce water consumption by approximately 13 times (20 ± 3.8 L/kg versus 250 ± 25 L/kg), but to lag behind conventional cultivation in energy consumption by 82 ± 11 times (90,000 ± 11,000 kJ/kg versus 1,100 ± 75 kJ/kg). Electricity productivity is 0.11…0.14 kg/(kWh).

5. For small-volume units, the recommended design parameters are substantiated: 3…4 tiers, 350…450 mm tier spacing, 4…6 L substrate per container, a calculated load of 30…50 kg per tier,

an optimal air-velocity range of 0.3…1.0 m/s, and an inter-tier temperature difference not exceeding 2 °C.

6. Coverage analysis of eleven normative documents against eight criteria showed coverage indices of 27.3% for building structures and air-exchange calculation, 18.2% for photosynthetic lighting quantities, and 9.1% for irrigation equipment. The coverage index is 0% for inter-tier temperature difference, air velocity above the canopy, illumination non-uniformity, and applicability to small-volume multi-tier construction.

7. To fill the identified gap, eight verifiable indicators are proposed for inclusion in a sectoral normative document: $\Delta T < 2$ °C; air velocity 0.3…1.0 m/s; PPFD 150…250 µmol/(m²·s); DLI 12…17 mol/(m²·day); illumination non-uniformity <20%; number of tiers 3…4; tier spacing 350…450 mm; and substrate volume 4…6 L/container.

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