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Anita C. Ezeagba, Danny D. Mann

Department of Biosystems Engineering, University of Manitoba, Winnipeg, Manitoba, Canada

Corresponding Author: Danny D. Mann, Department of Biosystems Engineering, University of Manitoba, 75 Chancellors Circle, Winnipeg, MB, R3T 5V6, Canada. E-mail: danny.mann@umanitoba.ca

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Corresponding Author: Danny D. Mann, Department of Biosystems Engineering, University of Manitoba, 75 Chancellors Circle, Winnipeg, MB, R3T 5V6, Canada. E-mail: danny.mann@umanitoba.ca

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Abstract

Vertical farming (VF) represents a transformative approach to agricultural production utilizing multi-tiered, controlled-environment systems, yet it introduces unique ergonomic challenges distinct from conventional agriculture. This literature review synthesizes current evidence on ergonomic issues in vertical farming systems, alongside evidence from indoor farming and broader controlled-environment agriculture (CEA) systems, examining musculoskeletal disorder (MSD) prevalence, risk factors, assessment methodologies, and intervention strategies. Agricultural workers in greenhouse and indoor farming environments experience MSD prevalence rates of 50.9% to 89.3%, with the lower back, shoulders, knees, and neck most commonly affected. Available evidence suggests that vertical farming may present distinctive ergonomic challenges, including multi-tiered configurations associated with overhead reaching, lower-tier access constraints, repetitive precision tasks, environmental stressors, and complex human-technology interactions. However, much of the current evidence is inferred from greenhouse and broader controlled-environment agriculture systems. While traditional ergonomic assessment tools (RULA, REBA, OWAS) and advanced methods (EMG) have been applied in agricultural contexts, their adaptation to vertical farming remains limited. Current interventions show promise through workspace optimization, tool redesign, automation, and participatory ergonomics approaches. However, significant knowledge gaps persist regarding longitudinal health outcomes, human-automation interaction, cognitive ergonomics, and socioeconomic dimensions specific to vertical

farming. This review highlights the emerging need for human-centered design principles in VF system development to ensure worker health, safety, and operational sustainability.

Key words: vertical farming; ergonomics; musculoskeletal disorders; controlled-environment agriculture; occupational health.

Introduction

The rise of vertical farming

Vertical farming has emerged as a promising solution to address global food security challenges, urbanization pressures, and environmental sustainability concerns. By stacking crops in vertical layers within controlled-environment facilities, VF systems achieve unprecedented space efficiency while reducing water consumption, eliminating pesticide use, and enabling year-round production independent of climate conditions (Lee *et al*., 2025; Kozai *et al*., 2020). As the vertical farming industry expands globally, with projections indicating substantial market growth over the coming decades, understanding and addressing the occupational health implications of this novel production system becomes increasingly critical (Kirkhorn *et al*. 2010; Benke and Tomkins, 2017).

Definition and classification of production systems

For clarity, this review adopts a hierarchical distinction between controlled-environment agricultural systems:

- **Controlled-environment agriculture (CEA)** refers broadly to agricultural production systems in which environmental conditions such as temperature, humidity, light, and nutrient delivery are actively regulated to optimize plant growth. This category includes greenhouses, indoor farming, and vertical farming systems.
- **Indoor farming** is a subset of CEA in which crops are grown entirely within enclosed structures, typically without reliance on natural sunlight, and with full environmental control through artificial lighting and climate systems. Indoor farming systems may be single-layer or multi-layer.
- **Vertical farming (VF)** represents a specialized subset of indoor farming characterized by multi-tiered or stacked crop production systems, often combined with high levels of automation, artificial lighting (e.g., LEDs), and space-optimized layouts.

While greenhouse systems are also part of CEA, they typically rely partially on natural sunlight and are not considered indoor farming or vertical farming in this review. This classification framework is used throughout the manuscript to distinguish between direct VF evidence and findings derived from related systems (Figure 1).

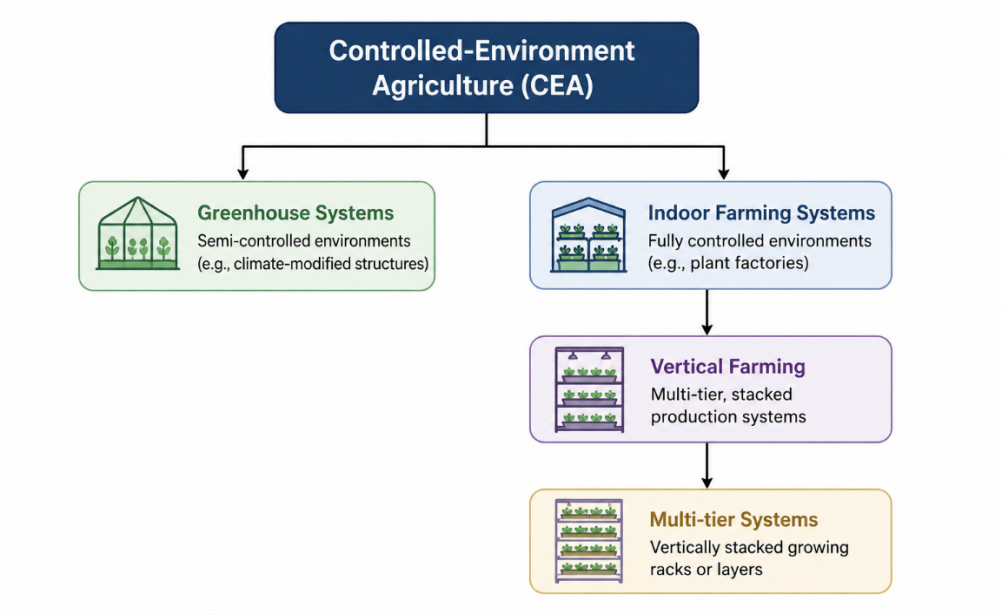


Figure 1. Classification framework of controlled-environment agriculture (CEA).

The ergonomic imperative

Despite technological advances in agricultural automation, vertical farming operations remain substantially labor-intensive, requiring human workers to perform tasks such as seeding, transplanting, monitoring, harvesting, and quality control. The unique spatial configurations, environmental conditions, and task demands of VF systems introduce ergonomic challenges that differ markedly from both conventional field agriculture and traditional greenhouse operations. Musculoskeletal disorders represent a significant occupational health burden in agriculture globally, with work-related MSDs constituting a leading cause of disability and lost productivity (Benos *et al*., 2020; Kirkhorn *et al*., 2010; Akbar *et al*., 2023). As vertical farming systems transition from experimental prototypes to large-scale commercial operations, ergonomic considerations must evolve from reactive injury prevention measures to proactive design criteria embedded within system architecture.

Review objectives and scope

This review synthesizes current evidence relevant to ergonomics in vertical farming systems by integrating the limited VF-specific literature with findings from greenhouse and broader controlled-environment agriculture (CEA) contexts. Where evidence is indirect, conclusions are presented cautiously and interpreted as hypotheses requiring validation in commercial VF operations. Specific objectives include: i) identifying and characterizing ergonomic challenges unique to vertical farming; ii) comparing VF ergonomics with conventional agricultural systems; iii) evaluating assessment methodologies applicable to VF contexts; iv) reviewing current intervention strategies and their effectiveness; v) identifying critical knowledge gaps; and vi) proposing future research directions to advance human-centered design in vertical farming.

Methodology

Review design

This study was conducted as a structured narrative review informed by PRISMA-style literature identification, screening, and selection procedures. A formal systematic review with meta-analysis was not undertaken because literature specifically addressing ergonomics in vertical farming systems remains limited, heterogeneous, and distributed across multiple disciplines including agricultural engineering, occupational health, ergonomics, greenhouse production, and controlled-environment agriculture (CEA).

Accordingly, a narrative synthesis approach was selected to integrate available evidence while maintaining a transparent and reproducible search and screening process.

Literature search strategy

A comprehensive literature search was performed between December 2025 and February 2026 using the following electronic databases: Scopus, Web of Science Core Collection, PubMed, and Google Scholar. These databases were selected to capture multidisciplinary evidence relevant to ergonomics, occupational health, engineering, and indoor agricultural systems.

Search strings combined Boolean operators (AND/OR) and included keywords such as “vertical farming,” “indoor farming,” “plant factory,” “controlled-environment agriculture,” “greenhouse agriculture,” “ergonomics,” “human factors,” “musculoskeletal disorders,” “occupational health,” “work-related musculoskeletal disorders,” “human-machine interaction,” and “automation

agriculture." An example of the search syntax used is ("vertical farming" OR "indoor farming" OR "plant factory") AND ("ergonomics" OR "musculoskeletal disorders" OR "occupational health"). Reference lists of key studies and relevant reviews were also manually searched to identify additional publications.

Eligibility criteria

Inclusion criteria: studies were included if they were peer-reviewed journal articles, conference proceedings, or authoritative institutional reports, published in English, and addressed worker ergonomics, musculoskeletal disorders, workload, occupational health, workplace design, or intervention strategies. Eligible studies focused on vertical farming, greenhouse production, indoor farming, or other controlled-environment agricultural systems and contained findings relevant to worker health or ergonomic risk factors.

Exclusion criteria: studies were excluded if they focused solely on crop yield, plant physiology, lighting, or agronomy without worker-related outcomes; were editorials, opinion papers, or non-substantive commentary; were duplicates; or had insufficient methodological detail or inaccessible full text.

Study selection process

All retrieved records were exported and duplicates removed. Titles and abstracts were screened for relevance, followed by full-text review of potentially eligible studies. Studies meeting the inclusion criteria were retained for final synthesis.

Because direct evidence on vertical farming ergonomics remains scarce, studies from greenhouse and indoor agricultural systems were included where findings were transferable to vertical farming work environments.

Data extraction and synthesis

Information extracted from included studies comprised the study setting and agricultural system, population and task characteristics, ergonomic exposures and risk factors, musculoskeletal outcomes, assessment tools used (e.g., RULA, REBA, OWAS, OCRA, EMG, and questionnaires), intervention strategies, and key findings relevant to vertical farming systems.

Findings were synthesized narratively under four major themes: ergonomic challenges specific to vertical farming, assessment methodologies and their applicability, intervention strategies and solutions, and research gaps and future directions. A summary of the included studies organized by these thematic categories is presented in Table 1.

PRISMA-informed search summary

The search process identified 126 records through database searching and 14 additional records through manual reference screening. After removal of duplicates, 104 records remained for title and abstract screening. Following screening, 52 full-text articles were assessed for eligibility. Of these, 31 studies met inclusion criteria and were included in the final review synthesis (Figure 2).

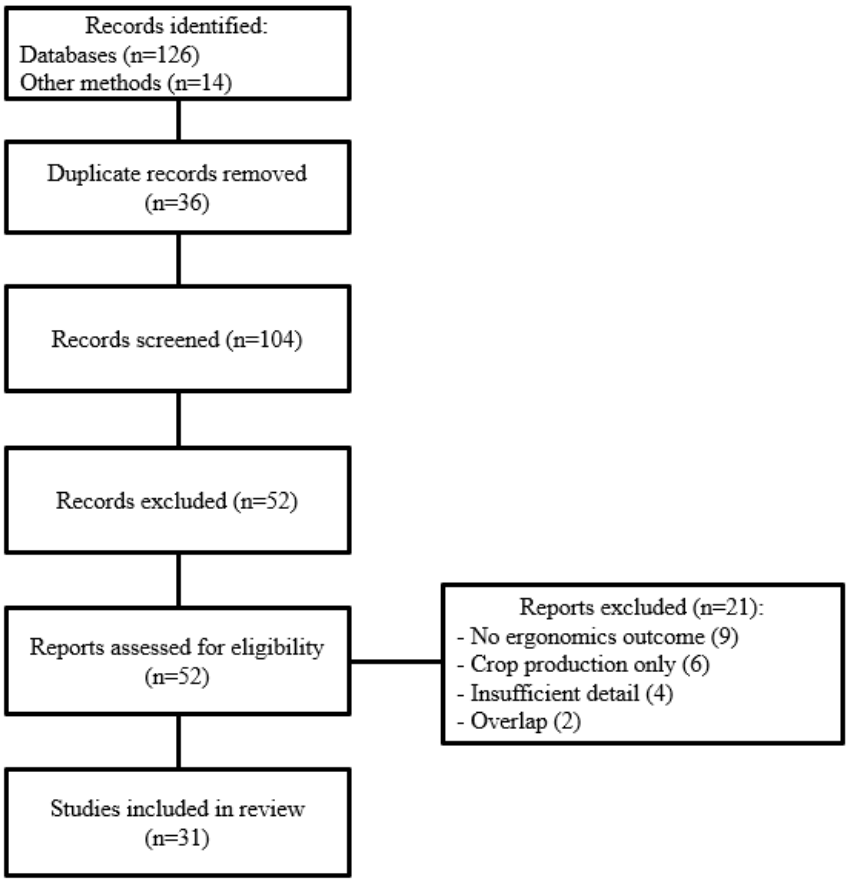


Figure 2. PRISMA-style flow diagram of literature selection process.

Musculoskeletal disorders in agriculture

Musculoskeletal disorders have reached epidemic proportions globally, with agricultural workers experiencing disproportionately high rates compared to other occupational sectors (Barneo-Alcántara *et al*., 2021). MSDs encompass a range of conditions affecting muscles, tendons, ligaments, nerves, and joints, typically resulting from cumulative exposure to ergonomic risk factors. In agricultural contexts, MSDs manifest primarily as low back pain, shoulder disorders, knee problems, and upper extremity conditions (Benos *et al*., 2020; Lee *et al*., 2011; Punnett and Wegman, 2004). In this review, a distinction is made between MSD symptoms (self-reported pain or discomfort), prevalence (proportion of workers reporting symptoms within a defined period), and ergonomic risk factors (workplace exposures such as repetition, posture, and force that contribute to MSD development).

The etiology of work-related MSDs in agriculture is multifactorial, involving biomechanical, physiological, psychosocial, and individual factors. Key biomechanical risk factors include repetitive movements, awkward postures (particularly stooping, kneeling, and overhead reaching), forceful exertions, static loading, and whole-body vibration (Shamsipour *et al*., 2025; Ramos-García *et al*., 2024). These risk factors interact with individual characteristics such as age, sex, physical fitness, and prior injury history to determine MSD susceptibility (Farahbakhsh *et al*., 2025).

Controlled-environment agriculture and worker health

Controlled-environment agriculture (CEA) encompasses a wide range of production systems, including greenhouses, indoor farms, and vertical farming facilities, each with distinct environmental controls and ergonomic implications. Greenhouse and indoor farming systems, while offering environmental control advantages, introduce specific occupational health challenges. Research in greenhouse vegetable production has documented high MSD prevalence rates, with studies reporting that 78.4% of greenhouse farmers experience musculoskeletal symptoms (Yao *et al*., 2016). The lower back emerges as the most commonly affected region (62.4%), followed by knees (41.9%), neck (22.9%), and shoulders (20.3%) (Yao *et al*., 2016).

Greenhouse work involves characteristic risk factors including prolonged bending, frequent lifting and carrying, repetitive upper limb movements, and sustained awkward postures (Gómez-Galán

et al., 2021; Kim *et al*., 2023). Specific tasks such as tomato training have been associated with distinctive occupational conditions, with one study identifying "tomato trainer's shoulder" as a prevalent disorder affecting 64.3% of workers over 12 months, attributed to highly repetitive (10,000-16,000 times per week) and static shoulder loading at or above shoulder height (Palmer, 1996).

Vertical farming: a distinct ergonomic context

Although vertical farming shares some characteristics with greenhouse and indoor agriculture, it differs in several important ways that may influence worker ergonomic exposures. These include multi-tier growing structures, higher spatial density, greater integration of automation, artificial lighting environments, and technology-intensive monitoring systems. However, empirical studies directly quantifying these exposures in VF settings remain limited. VF systems are frequently designed around plant growth optimization rather than human anthropometric variability, which may result in mismatches between system geometry and worker capabilities. Furthermore, VF operations emphasize precision agriculture techniques, requiring workers to perform detailed monitoring, data collection, and quality control tasks that impose cognitive demands alongside physical requirements. The integration of automation and robotics in VF systems introduces human-machine interaction considerations that extend beyond traditional agricultural ergonomics (Lee *et al*., 2025).

Conceptual framework for ergonomics in vertical farming systems

To address the multidimensional nature of ergonomic risk in vertical farming (VF), a conceptual framework is proposed to integrate the physical, cognitive, environmental, and technological factors influencing worker health and performance (Figure 3). This framework builds on the themes identified in the literature and reflects the socio-technical characteristics of VF systems described throughout this review (Kirkhorn *et al*., 2010; Parasuraman *et al*., 2000; Wickens *et al*., 2015).

At its core, the framework conceptualizes VF as a socio-technical system, where worker outcomes (e.g., musculoskeletal disorders, fatigue, productivity, and well-being) are shaped by the interaction of four primary domains.

Physical ergonomics

This domain includes biomechanical exposures such as repetitive movements, awkward postures (e.g., overhead reaching, stooping), forceful exertions, and static loading. In VF systems, multi-tier configurations and precision tasks redistribute physical demands across the upper and lower body rather than concentrating them solely on the lower back (Benos *et al*., 2020; Gómez-Galán *et al*., 2021; Kumar *et al*., 2023).

Cognitive ergonomics

VF operations introduce significant cognitive demands related to monitoring automated systems, interpreting data, performing quality control, and coordinating with technology. Mental workload, attention requirements, and decision-making processes represent critical but underexplored contributors to worker strain (Parasuraman *et al*., 2000; Wickens *et al*., 2015).

Environmental ergonomics

Controlled-environment conditions—including temperature, humidity, lighting, and air quality—affect both physiological strain and comfort. Unlike field agriculture, VF environments are artificially regulated, which may optimize plant growth but not necessarily human well-being (Gómez-Galán *et al*., 2021; Kumar *et al*., 2023).

Technological and human–machine interaction

Automation, robotics, and digital systems are integral to VF operations. These technologies can reduce physical workload but may introduce new ergonomic challenges related to interface design, system monitoring, maintenance tasks, and cognitive load (Cecchini *et al*., 2010; Parasuraman *et al*., 2000; Lee *et al*., 2025).

These domains are further influenced by organizational and task-level factors, including work scheduling, task design, training, and participatory practices. Together, these elements interact dynamically rather than independently. For example, automation may reduce physical strain but increase cognitive demands, while environmental conditions may exacerbate both physical fatigue and mental workload (Yao *et al*., 2016; Lee *et al*., 2011).

The framework emphasizes that ergonomic risk in VF is emergent, arising from the interaction between system components rather than from isolated factors. Consequently, effective intervention

strategies should adopt a systems-based approach, integrating engineering, organizational, and human-centered design principles rather than targeting single risk factors in isolation (Kirkhorn *et al*., 2010; Benos *et al*., 2020).

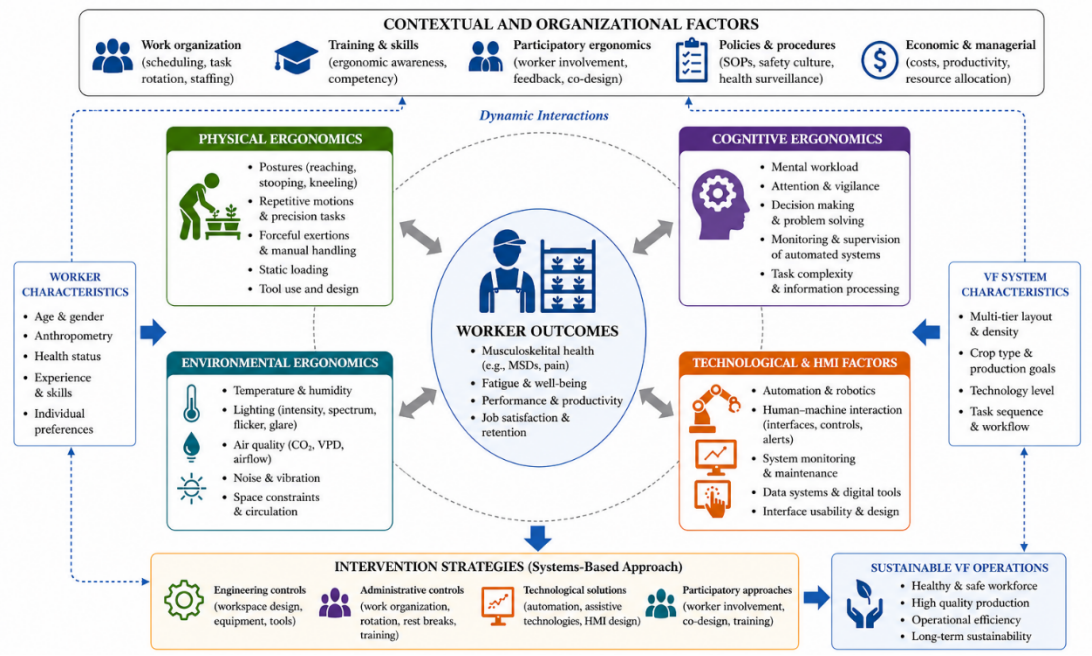


Figure 3. Conceptual framework of ergonomic factors in vertical farming systems.

Ergonomic challenges specific to vertical farming

Multi-tiered spatial configurations

The defining characteristic of vertical farming—stacked growing layers—likely creates important ergonomic challenges related to vertical reach requirements and access constraints, although direct observational evidence remains limited. In many commercial VF layouts, workers may need to access multiple tiers, potentially requiring overhead reaching for upper levels and stooping or kneeling for lower levels. Access to upper tiers often involves ladders or mobile platforms, introducing additional stability and fall-risk considerations. Research on greenhouse pruning operations demonstrates that working above shoulder height significantly increases physiological cost, with heart rate, oxygen consumption, energy expenditure, and perceived exertion all significantly elevated compared to work at elbow or shoulder height (Kumar *et al*., 2023).

The vertical dimension introduces postural demands that differ from ground-level field agriculture. Studies using postural assessment methods in greenhouse environments have identified high-risk

postures, with 50% of observed postures corresponding to RULA action level 3 (investigation and changes required soon) and 35% to level 4 (investigation and changes required immediately) (Gómez-Galán *et al*. 2021). The back and legs emerge as the most affected body regions, with OWAS assessments showing 16% high-risk and 1% very high-risk postures (Gómez-Galán *et al*. 2021).

Repetitive precision tasks

Vertical farming operations involve several repetitive precision tasks, including seeding, transplanting, harvesting, and inspection, that require fine motor control and sustained upper limb activity. Research on muscle activation patterns in vertical farming tasks has revealed that all eight major upper limb muscles are engaged during common VF activities, with anterior deltoids showing the highest activation levels ($p<0.001$) (Lee *et al*., 2025). During harvesting operations specifically, flexor carpi ulnaris demonstrates significantly higher activation ($p<0.05$), indicating substantial demands on forearm and wrist musculature (Lee *et al*., 2025).

The repetitive nature of VF tasks parallels concerns identified in conventional greenhouse operations. Studies of tomato sorting operations using the OCRA (Occupational Repetitive Actions) index have documented unacceptable risk levels (OCRA index >3.5) for workers performing manual sorting, with exposure indices exceeding 20 (Cecchini *et al*., 2010). These findings underscore the MSD risk associated with high-frequency, repetitive upper limb activities characteristic of precision agriculture tasks.

Environmental factors

The controlled-environment nature of vertical farming creates unique environmental exposures that influence worker comfort, fatigue, and injury risk. While VF systems eliminate weather-related variability, they introduce artificial environmental conditions that may pose ergonomic challenges. Temperature and humidity control, essential for optimal plant growth, may not align with human thermal comfort requirements. Artificial lighting systems—especially high-intensity LED arrays—not only introduce novel visual environments that may contribute to eye strain and fatigue but also raise important visual ergonomics considerations beyond thermal conditions, including glare, spectral effects, and visual fatigue. Research in greenhouse environments has identified environmental factors as significant contributors to worker discomfort and MSD risk.

The combination of high temperature, humidity, and physical workload creates elevated physiological strain, with studies documenting significant increases in heart rate and energy expenditure under greenhouse conditions (Kumar *et al*., 2023). While specific research on VF environmental ergonomics remains limited, the enclosed nature of VF facilities and the intensity of environmental control systems suggest potential for similar or amplified environmental stressors.

Technology integration and human-machine interaction

Vertical farming systems increasingly incorporate automation, robotics, and digital monitoring technologies, creating complex human–machine interaction scenarios. Workers must interface with automated seeding systems, robotic harvesting equipment, climate control interfaces, and data management platforms. While automation holds promise for reducing physical workload, it introduces significant cognitive demands related to system monitoring, interpretation of data, and coordination with automated processes (Parasuraman *et al*., 2000; Wickens *et al*., 2015; Benos *et al*., 2023).

At the task level, VF workers are required to continuously monitor environmental control systems (e.g., temperature, humidity, nutrient delivery), interpret real-time sensor data, and respond to system alerts or anomalies. These activities involve sustained attention, vigilance, and rapid decision-making under time constraints. In addition, precision tasks such as quality grading and defect detection require visual discrimination and cognitive vigilance, particularly under artificial lighting conditions.

To further clarify the distribution of cognitive demands across VF operations, Table 2 summarizes the primary cognitive requirements associated with common vertical farming tasks and their potential ergonomic implications.

Importantly, these cognitive demands often occur simultaneously with physical tasks, such as harvesting or transplanting across multiple tiers. This creates dual-task conditions that divide attentional resources between physical execution and system monitoring, increasing the likelihood of errors and reducing situational awareness. Evidence from human–automation and human–robot interaction research indicates that increased mental workload can offset reductions in physical strain and affect overall system performance (Yerebakan *et al*., 2025).

Task-based ergonomic analysis in vertical farming

Vertical farming operations consist of a series of discrete but repetitive tasks, each associated with distinct ergonomic exposures. While prior sections describe general risk factors, a task-based perspective provides more actionable insight for assessment and intervention design (Benos *et al*., 2020; Kirkhorn *et al*., 2010).

Based on available literature and typical VF operational workflows, key task categories include seeding and propagation, transplanting, crop maintenance, harvesting, monitoring and inspection, and system maintenance. Each of these tasks is characterized by specific combinations of physical, postural, and cognitive demands that contribute to overall ergonomic risk (Lee *et al*., 2025; Kumar *et al*., 2023; Gómez-Galán *et al*., 2021).

Table 3 presents a structured overview of these common vertical farming tasks, highlighting their typical activities, associated ergonomic risk factors, and the primary body regions affected.

Together, these task-specific exposures illustrate how ergonomic risks in vertical farming arise from the interaction of repetitive movements, postural constraints, and, in some cases, cognitive demands, reinforcing the need for targeted, task-level ergonomic assessment and intervention strategies (Parasuraman *et al*., 2000; Wickens *et al*., 2015).

Seeding and propagation

Seeding and propagation tasks typically involve repetitive fine motor movements, including seed placement and tray preparation. These activities may result in cumulative strain in the fingers, wrists, and forearms, particularly when performed at high throughput rates. Static seated or standing postures during tray preparation may also contribute to neck and upper back discomfort (Benos *et al*., 2020; Lee *et al*., 2011).

Transplanting

Transplanting tasks involve transferring seedlings between growth stages and often require frequent bending, reaching, and light lifting. In VF systems, transplanting may occur at multiple vertical levels, increasing variability in posture and contributing to lower back and shoulder strain (Lee *et al*., 2011; Gómez-Galán *et al*., 2021).

Crop maintenance

Crop maintenance tasks such as pruning, training, and spacing plants frequently involve repetitive upper limb movements and sustained arm elevation, particularly in upper-tier systems. Evidence from greenhouse studies suggests that such overhead work is associated with increased shoulder loading and fatigue, which is likely transferable to VF contexts (Palmer, 1996; Kumar *et al*., 2023).

Harvesting

Harvesting represents one of the most ergonomically demanding tasks in VF systems, combining repetitive cutting or picking motions with awkward postures and material handling. EMG-based studies in VF contexts indicate substantial activation of upper limb musculature during harvesting tasks, particularly in the forearm and shoulder regions (Lee *et al*., 2025; Cecchini *et al*., 2010).

Monitoring and inspection

Monitoring tasks involve visual inspection of plant health, data recording, and system checks. While physically less demanding, these tasks introduce prolonged static postures, neck flexion, and visual strain, as well as cognitive workload associated with decision-making and system monitoring (Parasuraman *et al*., 2000; Wickens *et al*., 2015; Lee *et al*., 2025).

System maintenance

Maintenance tasks, including cleaning, equipment adjustment, and troubleshooting, may involve forceful exertions, awkward postures, and work in confined spaces. These tasks are often intermittent but may present high acute ergonomic risk (Kirkhorn *et al*., 2010; Benos *et al*., 2020).

Expanded ergonomic risk dimensions in vertical farming

In addition to the primary ergonomic challenges discussed above, several critical but underexplored risk dimensions influence worker health and performance in vertical farming systems. These include manual material handling, access to multi-tier systems, visual ergonomics under artificial lighting, anthropometric variability, and psychosocial and organizational factors (Kirkhorn *et al*., 2010; Lee *et al*., 2025).

Manual material handling and load movement

Although vertical farming is often perceived as less physically demanding than field agriculture, manual material handling remains a significant component of VF operations. Workers frequently lift, carry, and transport trays, growing modules, nutrient containers, and harvested produce. While individual loads may be lighter than in conventional agriculture, the frequency and cumulative exposure may still contribute to musculoskeletal strain, particularly in the lower back and upper extremities (Lee *et al*., 2011; Benos *et al*., 2020).

Repetitive lifting combined with awkward postures—especially when handling materials at different vertical levels—may increase injury risk. Evidence from greenhouse and agricultural systems indicates that manual handling is a primary contributor to back disorders, suggesting similar risks may be present in VF contexts (Baron *et al*., 2001; Kirkhorn *et al*., 2010).

Access to multi-tier systems

Accessing vertically stacked growing systems presents unique ergonomic and safety challenges. Workers may rely on ladders, step platforms, or mobile access systems to reach upper tiers, while lower tiers may require kneeling, crouching, or working in confined spaces. These access constraints can lead to unstable postures, increased fall risk, and cumulative joint loading (Gómez-Galán *et al*., 2021; Kumar *et al*., 2023).

The design of access systems is therefore critical. Poorly designed ladders or narrow aisles may restrict movement and increase ergonomic strain. Despite its importance, empirical research on safe and ergonomic access strategies in VF environments remains limited (Lee *et al*., 2025; Shamsipour *et al*., 2025).

Visual ergonomics under artificial lighting

Vertical farming environments rely heavily on artificial lighting systems, particularly high-intensity LEDs with specific spectral compositions. While optimized for plant growth, these lighting conditions may not align with human visual comfort. Workers performing detailed inspection or harvesting tasks may experience visual fatigue, glare, reduced contrast sensitivity, and eye strain (Kozai *et al*., 2020; Wickens *et al*., 2015).

Prolonged exposure to artificial lighting conditions, particularly in enclosed environments, may also affect circadian rhythms and overall well-being. Research on visual ergonomics in VF contexts is scarce, representing an important emerging area for investigation (Lee *et al*., 2025).

Anthropometric variability and inclusive design

Vertical farming systems are often designed primarily around crop requirements rather than human anthropometry. Fixed tier heights, reach distances, and workstation layouts may not accommodate the full range of worker body sizes, strengths, and mobility levels (ISO, 2016; Kumar *et al*., 2023). Failure to account for anthropometric variability can result in systematic exposure to awkward postures, particularly for shorter or taller workers. Inclusive design principles—such as adjustable work heights, adaptable access systems, and consideration of diverse worker populations—are essential to ensure equitable and safe working conditions. This issue is particularly important given the diversity of agricultural workforces globally (ISO, 2016; Yao *et al*., 2016).

Psychosocial and organizational factors

Ergonomic risk in vertical farming extends beyond physical exposures to include psychosocial and organizational dimensions. Factors such as work pace, production targets, task repetition, job control, and cognitive workload can influence both physical and mental health outcomes (Kirkhorn *et al*., 2010; Punnett and Wegman, 2004).

The integration of automation and digital monitoring systems may increase cognitive demands, requiring sustained attention, decision-making, and system oversight. Additionally, repetitive and monotonous tasks may contribute to mental fatigue and reduced job satisfaction (Parasuraman *et al*., 2000; Wickens *et al*., 2015).

Evidence from occupational health research indicates that psychosocial stressors can interact with physical risk factors to exacerbate MSD risk. However, these dimensions remain largely unexplored in vertical farming contexts (Punnett and Wegman, 2004; Kirkhorn *et al*., 2010).

Comparison with conventional agricultural ergonomics

In the absence of direct ergonomic comparison studies between conventional field agriculture and vertical farming systems, the comparisons presented in this section are primarily conceptual and

informed in part by evidence from greenhouse and broader controlled-environment agriculture (CEA) contexts (Benos *et al*., 2020; Gómez-Galán *et al*., 2021; Lee *et al*., 2025).

Postural demands: field *vs* vertical farming

Conventional field agriculture is characterized by prolonged stooping, bending, and kneeling, particularly for ground-level crop cultivation and harvesting. Research on ground-level crop harvesting has documented that workers maintain full trunk flexion (>90 degrees) for extended periods, leading to fatigue and spinal instability (Mirka *et al*., 2003). This sustained flexion posture can cause changes in viscoelastic structures supporting the spinal column, increasing injury risk during subsequent lifting tasks (Mirka *et al*., 2003; Punnett and Wegman, 2004).

In contrast, vertical farming introduces a broader range of postural demands across the vertical plane. While lower-tier access requires similar stooping and bending as field agriculture, upper-tier access necessitates overhead reaching and sustained elevated arm postures that are rarely encountered in field work. This vertical diversity of postural demands may redistribute musculoskeletal disorder (MSD) risk across multiple body regions rather than concentrating it primarily in the lower back.

To contextualize these differences within the broader evidence base, Table 4 presents a conceptual comparison of worker demands across agricultural production systems—including field agriculture, greenhouse controlled-environment agriculture (CEA), and vertical farming—highlighting the availability and strength of supporting evidence for each domain.

Environmental exposures: outdoor *vs* controlled environments

Field agriculture exposes workers to weather variability, solar radiation, temperature extremes, and precipitation, creating seasonal patterns of environmental stress. Greenhouse and vertical farming eliminate these weather-related exposures but introduce artificial environmental conditions with their own ergonomic implications. The enclosed nature of CEA facilities can create elevated temperature and humidity levels, particularly in greenhouses with limited climate control (Gómez-Galán *et al*., 2021).

Vertical farming facilities, with advanced HVAC systems, theoretically offer superior environmental control compared to traditional greenhouses. However, the energy-intensive nature of VF and the heat generated by high-density LED lighting systems may create localized thermal

stress. The absence of natural ventilation in sealed VF facilities also raises concerns about air quality and the accumulation of airborne contaminants, though specific research on these factors in VF contexts is lacking.

Task characteristics: manual labor *vs* precision agriculture

Conventional field agriculture emphasizes heavy manual labor, including lifting, carrying, and manipulating heavy loads. Studies have documented that agricultural workers frequently handle loads ranging from 20-80 kg, with melon harvesting involving particularly heavy lifting demands (Lee *et al*., 2011). This heavy load handling contributes to high rates of back injuries, which account for one-quarter of all agricultural injuries causing missed work (Baron *et al*., 2001).

Vertical farming, while not eliminating heavy lifting entirely, shifts emphasis toward precision tasks requiring fine motor control, visual acuity, and sustained attention. The smaller scale of VF operations and the use of growing trays or modules may reduce individual load weights compared to field agriculture. However, the repetitive nature of precision tasks and the sustained static postures required for detailed work introduce different MSD risk profiles, with greater emphasis on upper extremity and neck disorders.

MSD prevalence patterns

Comparative analysis of MSD prevalence across agricultural contexts reveals both commonalities and distinctions. In Southeast Asian agricultural populations, systematic review evidence indicates extremely high WMSD prevalence: Thailand (78.31%), Indonesia (81.27%), and Malaysia (88.39%) (Akbar *et al*. 2023). In greenhouse-specific populations, prevalence rates range from 50.9% to 89.3%, with male workers showing particularly high rates (Farahbakhsh *et al*., 2025; Yao *et al*., 2016).

Across agricultural contexts, the lower back consistently emerges as the most affected body region, with prevalence rates ranging from 26.7% to 76% depending on crop type and production system (Lee *et al*., 2011; Yao *et al*., 2016; Punnett and Wegman, 2004). However, the relative prevalence of upper extremity disorders varies by production system. Greenhouse tomato trainers, for example, show dramatically elevated shoulder disorder rates (64.3% over 12 months) compared to other greenhouse workers (Palmer, 1996), suggesting that task-specific exposures in CEA systems can create distinctive MSD patterns.

Assessment methodologies and their application

Observational postural assessment methods

RULA (rapid upper limb assessment)

RULA has been widely applied in agricultural ergonomics to assess upper limb and neck postural loading. In greenhouse pepper cultivation, RULA assessments have identified high-risk postures, with 50% of observed postures at action level 3 and 35% at level 4 (Gómez-Galán *et al*., 2021). The method's focus on upper body postures makes it particularly relevant for vertical farming tasks involving overhead reaching and repetitive upper limb movements.

However, RULA's application in dynamic agricultural environments presents challenges. The method was originally developed for static workstation assessment and may not fully capture the variability and complexity of agricultural tasks. Some research suggests that RULA data may overestimate risks in agricultural contexts, as workers may not exhibit the functional limitations or sick leave patterns predicted by high RULA scores (Gómez-Galán *et al*., 2021).

REBA (rapid entire body assessment)

REBA provides whole-body postural assessment, making it suitable for evaluating the diverse postural demands of vertical farming. Studies of manual farming operations have used REBA to document high-risk postures, with pre-intervention scores averaging 9.7 (high-risk category) (Nerona *et al*., 2023). REBA has been applied across various agricultural tasks in Korean farming contexts, including melon cultivation, strawberry production, and grape farming (Lee *et al*., 2011). The effectiveness of REBA in capturing vertical farming ergonomics is supported by its ability to assess both upper and lower body postures, load handling, and coupling factors. Research on oriental melon farming identified high-risk tasks including moving boxes, transplanting, and picking, all involving squatting postures that REBA can effectively evaluate (Bae *et al*., 2011). However, REBA's application requires trained observers and may be time-intensive for comprehensive workplace assessment.

OWAS (Ovako working posture assessment system)

OWAS focuses on whole-body postures with particular emphasis on back, arms, and legs, making it applicable to agricultural work involving varied postures. In greenhouse pepper cultivation, OWAS assessments revealed 53% normal postures, 30% medium risk, 16% high risk, and 1% very

high risk, with the back and legs most affected (Gómez-Galán *et al*., 2021). OWAS has also been applied to harvest cart operations, demonstrating its utility for evaluating agricultural equipment and workstation design (Baron *et al*., 2001).

The categorical nature of OWAS (classifying postures into discrete categories) provides simplicity but may lack the sensitivity to detect subtle postural variations important in precision agriculture tasks. Additionally, OWAS was developed for industrial settings and may not fully account for the dynamic, variable nature of agricultural work environments.

OCRA (occupational repetitive actions)

OCRA specifically assesses repetitive upper limb tasks, making it highly relevant for vertical farming operations involving repetitive harvesting, sorting, and quality control. Research on tomato sorting has used OCRA to document unacceptable risk levels (OCRA index >3.5) for manual sorting operations (Cecchini *et al*., 2010). The method's focus on action frequency, force, posture, and recovery time provides comprehensive evaluation of repetitive task risks.

OCRA's application in vertical farming contexts could be particularly valuable for assessing tasks such as selective harvesting, seedling transplanting, and quality inspection. However, OCRA requires detailed task analysis and timing data, which may be challenging to collect in dynamic production environments.

These assessment methods are particularly valuable when applied at the task level, enabling identification of high-risk activities such as harvesting, transplanting, and overhead crop maintenance.

Physiological assessment methods

Physiological measures provide objective quantification of physical workload and strain. Research on greenhouse pruning has employed heart rate monitoring, oxygen consumption measurement, and energy expenditure assessment to evaluate physiological costs of work at different heights and distances (Kumar *et al*., 2023). These studies demonstrate that physiological parameters increase significantly with working height (particularly above shoulder level) and horizontal reach distance (Kumar *et al*., 2023).

The Rating of Perceived Exertion (RPE) serves as a subjective complement to objective physiological measures. Studies have shown that RPE correlates strongly with physiological

parameters and can be predicted from heart rate and other measured variables using multiple regression analysis (Kumar *et al*., 2023). The combination of objective physiological measures and subjective RPE provides comprehensive assessment of physical workload in agricultural contexts.

Electromyography (EMG)

Surface electromyography enables direct measurement of muscle activation patterns, providing insights into muscular demands of specific tasks. Recent research on vertical farming tasks has employed EMG to assess activation of eight upper limb muscles during common VF activities (Lee *et al*., 2025). This study revealed that anterior deltoids show the highest activation levels across tasks, while flexor carpi ulnaris demonstrates significantly elevated activation during harvesting (Lee *et al*., 2025).

EMG assessment of ground-level crop harvesting has documented muscle activity patterns in back extensors, knee extensors, and knee flexors across various trunk and knee angles (Mirka *et al*. 2003). These findings demonstrate EMG's capability to identify specific muscular demands and inform targeted intervention strategies. However, EMG requires specialized equipment and expertise, limiting its practical application for routine workplace assessment.

Questionnaire-based assessments

Nordic musculoskeletal questionnaire

The Nordic Musculoskeletal Questionnaire (NMQ) represents the most widely used tool for MSD symptom surveillance in agricultural populations. Studies have employed the NMQ to document MSD prevalence in greenhouse workers (Farahbakhsh *et al*., 2025), tomato industry workers (Palmer, 1996), and diverse agricultural populations (Yao *et al*., 2016). The questionnaire's standardized format enables comparison across studies and populations, while its focus on specific body regions facilitates identification of task-specific MSD patterns.

Modified versions of the NMQ have been adapted for agricultural contexts, incorporating questions about specific work tasks, exposures, and risk factors (Yao *et al*., 2016). These adaptations enhance the questionnaire's relevance for agricultural ergonomics research while maintaining comparability with the standard NMQ format.

Agricultural-specific assessment tools

Recognition of agriculture's unique ergonomic challenges has prompted development of specialized assessment tools. The Agricultural Whole-Body Assessment (AWBA) checklist was specifically designed for investigating work-related whole-body disorders in farming (Kong *et al*., 2015). Such tools aim to capture the distinctive characteristics of agricultural work, including seasonal variability, diverse task demands, and outdoor environmental exposures.

However, the applicability of field-agriculture-focused tools to vertical farming contexts remains uncertain. The controlled-environment, precision-agriculture nature of VF may require adapted or novel assessment approaches that account for multi-tiered spatial configurations, human-automation interaction, and the cognitive demands of technology-intensive production systems.

Methodological challenges and gaps

Despite the availability of diverse assessment methods, significant challenges persist in their application to vertical farming contexts. Most existing tools were developed for industrial or traditional agricultural settings and may not fully capture VF-specific exposures. The dynamic nature of VF work, involving frequent transitions between tiers and tasks, complicates observational assessment. The integration of automation and digital technologies introduces cognitive and human-factors dimensions not addressed by traditional physical ergonomics assessment tools.

A systematic review of observational techniques for ergonomic risk assessment in farming identified a shortage of specific techniques tailored to agricultural occupations (Shamsipour *et al*., 2025). This gap is even more pronounced for vertical farming, where the unique spatial configurations, environmental conditions, and technology integration create assessment challenges not encountered in conventional agriculture. Future research must address these methodological gaps to enable effective ergonomic evaluation and intervention in VF systems.

Collectively, these limitations suggest that no single existing ergonomic assessment method adequately captures the combined physical, cognitive, and spatial demands of vertical farming work. A hybrid assessment approach, integrating observational, physiological, and questionnaire-based methods, may therefore be most appropriate in current VF contexts.

Current interventions and solutions

Effective ergonomic interventions in vertical farming should be task-specific—targeting high-risk activities such as harvesting (repetitive strain), transplanting (bending and reaching), and maintenance (forceful exertion and awkward postures), while also addressing not only postural and repetitive risks, but broader factors including manual material handling, access design, visual ergonomics, and organizational considerations. Interventions targeting these expanded risk dimensions may include mechanical aids for material handling, improved ladder and platform design, lighting systems optimized for both plant growth and human vision, adjustable workstations to accommodate anthropometric diversity, and organizational strategies to manage workload and cognitive demands.

Engineering controls and workspace optimization

Engineering interventions targeting workspace design and equipment modification represent primary strategies for MSD prevention. Research on greenhouse pruning has emphasized the need for workspace optimization to minimize overhead reaching and excessive horizontal distances (Kumar *et al*., 2023). Studies demonstrate that physiological cost and perceived exertion increase significantly with working height and reach distance, indicating clear targets for workspace redesign (ISO 2016; Kumar *et al*., 2023).

Practical engineering solutions documented in agricultural contexts include height-adjustable platforms, which enable workers to maintain neutral postures while accessing elevated work areas (Palmer, 1996). For ground-level work, ergonomic interventions such as weeding stands that elevate work surfaces have successfully reduced stooping requirements (Baron *et al*., 2001). In vertical farming contexts, these principles suggest the value of adjustable-height growing systems, mobile platforms, or mechanized tier-access solutions that bring work to comfortable working heights rather than requiring workers to adapt to fixed tier spacing.

Tool design and modification

Tool redesign represents a cost-effective intervention strategy with demonstrated effectiveness in agricultural settings. Research on pruning tools has shown differential effects of tool design on physiological parameters and perceived exertion (Kumar *et al*., 2023). Specific tool modifications documented in agricultural contexts include:

- Modified berry rakes with added handles, larger diameters, or stand-up designs to address stooped postures and pinch grips (Baron *et al*., 2001)
- Power cutters to reduce repetitive gripping forces for woody plant cutting (Baron *et al*., 2001)
- Electric scissors to reduce finger grip force and hand pressure in grape cultivation (Lee *et al*., 2011)
- Smaller, lighter harvesting containers to reduce load weights and carrying strain (Baron *et al*., 2001)

For vertical farming applications, tool design considerations should address the precision requirements of VF tasks while minimizing repetitive strain. Ergonomic hand tools for selective harvesting, lightweight containers with optimal handle designs, and powered assist devices for repetitive tasks represent promising directions for VF-specific tool development.

Automation and mechanization

Automation offers potential to eliminate or reduce exposure to high-risk tasks, though implementation must be carefully designed to avoid introducing new ergonomic challenges. Research on tomato sorting has identified optical sorters as an appropriate intervention to replace manual sorting, reducing WMSD risk while providing financial and quality control benefits (Cecchini *et al*., 2010). Historical attempts at automating tomato training using wire, hook, and pulley systems were unsuccessful (Palmer, 1996), highlighting the importance of practical, user-centered automation design.

In Korean agricultural contexts, development of specialized equipment has shown promise for reducing ergonomic risks. Small and large harvesting/transporting vehicles have reduced heavy handling demands, while improved reflective film machines have decreased manual material handling (Lee *et al*., 2011). Rail working chairs and multi-layer rotating worktables have improved REBA scores and productivity for tasks like grape pinching and strawberry packing (Lee *et al*., 2011).

In vertical farming, automation strategies may be particularly relevant for tasks suspected to involve elevated MSD risk; however, empirical intervention studies in VF settings are still needed. Automated seeding, transplanting, and harvesting systems are already being developed for VF applications. However, the ergonomic implications of human-automation interaction—including

system monitoring, maintenance, and intervention requirements—must be carefully considered to ensure that automation genuinely reduces rather than transforms worker burden.

Ergonomic furniture and support devices

Specialized ergonomic furniture can enable workers to maintain neutral postures during prolonged tasks. Research on manual farming in the Philippines developed and tested an ergonomic farmer's chair designed to reduce postural strain during planting and harvesting (Nerona, 2023). The intervention significantly reduced REBA scores from 9.7 (high-risk) to 6.4 (medium-risk), demonstrating substantial risk reduction (Nerona, 2023). The chair incorporated features including a foldable backrest, adjustable height, and mobility support (Nerona, 2023).

Similar principles apply to vertical farming, where workers may spend extended periods at specific tiers performing detailed tasks. Adjustable-height work seats, mobile platforms with integrated seating, and ergonomic standing supports could enable workers to maintain neutral postures while performing precision tasks at various heights. The key is ensuring that support devices are practical for the dynamic, multi-tier nature of VF work rather than constraining worker mobility.

Participatory ergonomics approaches

Participatory ergonomics, involving workers directly in identifying problems and developing solutions, has demonstrated effectiveness in agricultural settings. Research on ergonomic interventions for farm workers has documented that ergonomics teams involving both workers and managers led to better solutions and reduced injuries by over 50% (Baron *et al*., 2001). A case study of participatory ergonomic interventions in a Korean farming organization demonstrated the value of worker involvement in improving agricultural work environments (Kee, 2022).

The participatory approach offers several advantages: workers possess intimate knowledge of task demands and practical constraints; worker involvement increases intervention acceptance and compliance; and participatory processes can identify low-cost, practical solutions that might be overlooked by external experts. For vertical farming, participatory ergonomics could be particularly valuable given the novelty of VF systems and the limited existing knowledge base regarding VF-specific ergonomic challenges.

Administrative controls and work organization

Administrative interventions targeting work scheduling, task rotation, and work-rest cycles complement engineering controls. Research has identified prolonged work duration as a significant MSD risk factor, with workers performing more than 10 hours daily showing elevated risk (OR=1.32) (Yao *et al*., 2016). Task rotation strategies can reduce cumulative exposure to specific risk factors, though effectiveness depends on ensuring that rotation genuinely provides recovery rather than simply exposing workers to multiple risk factors.

Training and education represent essential administrative interventions. Studies have documented the value of muscular power and flexibility strengthening education, with complex exercise programs decreasing pain and improving physical fitness among elderly farmers (Lee *et al*. 2011). For vertical farming, training should address proper lifting techniques, optimal work methods for multi-tier access, and recognition of early MSD symptoms to enable timely intervention.

Intervention effectiveness and limitations

Although numerous ergonomic interventions have been proposed, their effectiveness must be interpreted cautiously. Much of the available evidence is derived from observational studies, case reports, or before–after designs without appropriate controls, limiting the ability to establish causal relationships between interventions and reductions in musculoskeletal disorders (MSDs) (Benos *et al*., 2020; Gómez-Galán *et al*., 2021).

In addition, many interventions demonstrate improvements in surrogate outcomes such as postural scores (e.g., REBA, RULA) or perceived exertion, but fewer studies report meaningful reductions in injury incidence, lost work time, or long-term health outcomes (Gómez-Galán *et al*., 2021; Kumar *et al*., 2023). This raises concerns about the extent to which commonly used ergonomic assessment tools capture clinically relevant improvements in worker health.

A further limitation is the context dependency of interventions. Strategies shown to be effective in conventional agriculture or greenhouse systems may not translate directly to vertical farming due to differences in spatial configuration, task structure, and technology integration (Palmer, 1996; Lee *et al*., 2011). For example, while adjustable platforms may reduce overhead reaching, their feasibility in high-density, multi-tier VF systems may be constrained by space, cost, or workflow disruption.

Automation, often presented as a high-impact solution, also warrants critical consideration. While it can reduce exposure to repetitive or physically demanding tasks, it may simultaneously introduce new ergonomic risks related to cognitive workload, system monitoring, and human–machine interaction (Cecchini *et al*., 2010; Parasuraman *et al*., 2000). Without careful design, automation may shift rather than eliminate worker burden.

Moreover, many interventions target single risk factors in isolation, whereas MSDs in agricultural systems are inherently multifactorial (Yao *et al*., 2016; Benos *et al*., 2020). This suggests that multi-component interventions, integrating engineering, organizational, and participatory approaches, are more likely to produce meaningful and sustained improvements. However, robust evidence evaluating such integrated strategies remains scarce (Benos *et al*., 2020).

Finally, there is a notable absence of longitudinal studies assessing the durability of intervention effects over time. Given the cumulative nature of MSDs, short-term improvements in posture or workload may not translate into long-term health benefits (Kirkhorn *et al*., 2010). This highlights the need for more rigorous, longitudinal, and VF-specific intervention research to establish evidence-based best practices.

Critical knowledge gaps in the literature

Vertical farming-specific research

The most significant evidence gap identified in this review is the scarcity of ergonomics research conducted directly in operational vertical farming facilities. Most current understanding is extrapolated from greenhouse, indoor farming, or broader agricultural studies. Consequently, several proposed VF-specific risks remain plausible but insufficiently validated. Only one identified study specifically examined muscle activation patterns in vertical farming tasks (Lee *et al*., 2025), highlighting the critical need for VF-focused ergonomics research.

Longitudinal health outcome studies

Most existing research employs cross-sectional designs that document MSD prevalence and risk factors at a single time point. Longitudinal studies tracking worker health outcomes over time are notably scarce. Such studies are essential for understanding the natural history of MSDs in VF contexts, identifying critical exposure thresholds, and evaluating the long-term effectiveness of interventions. The chronic nature of MSDs, with symptoms developing gradually over months or

years of exposure, necessitates longitudinal research designs that current literature largely lacks (Kirkhorn *et al*., 2010).

Human-automation interaction

As vertical farming increasingly incorporates automation and robotics, understanding the ergonomic implications of human-automation interaction becomes critical. Current literature provides minimal guidance on optimal task allocation between humans and machines, design of human-machine interfaces for VF systems, or the cognitive demands of monitoring and managing automated systems. Research is needed to ensure that automation genuinely reduces worker burden rather than introducing new forms of physical or cognitive strain.

Cognitive ergonomics and mental workload

Existing agricultural ergonomics research overwhelmingly emphasizes physical exposures, with comparatively limited attention to cognitive demands (Benos *et al*., 2020; Kirkhorn *et al*., 2010). However, the operational characteristics of vertical farming suggest that cognitive workload is a central component of ergonomic risk rather than a secondary consideration, particularly as VF systems increasingly rely on automation, digital monitoring, and human–machine coordination (Benos *et al*., 2023; Yerebakan and Hu, 2024).

In VF systems, workers frequently engage in tasks requiring sustained monitoring of automated processes, interpretation of environmental and crop performance data, and coordination with semi-autonomous technologies. These activities introduce multiple dimensions of cognitive load, including mental workload, attentional demand, vigilance, trust calibration, and decision-making complexity (Legler, 2025). Unlike conventional agriculture, where cognitive demands are often intermittent, VF environments may require continuous vigilance, particularly in highly automated facilities.

The interaction between cognitive and physical demands is especially important. Workers often perform manual tasks—such as harvesting or inspection—while simultaneously monitoring system performance or responding to alerts. This dual-task condition may increase the likelihood of errors, reduce situational awareness, and contribute to both acute safety risks and chronic fatigue. Recent agricultural human–robot collaboration research has shown that collaborative robotic systems can influence both biomechanical and cognitive workload, and that reliability

problems can reduce or reverse expected workload benefits (Yerebakan *et al*., 2025). More broadly, human factors research indicates that elevated cognitive workload can impair performance and increase error risk in complex, technology-mediated environments (Carissoli *et al*., 2024).

Despite these considerations, empirical measurement of cognitive workload in VF contexts is almost entirely absent. No identified studies in this review have applied established tools such as NASA-TLX, eye-tracking, or cognitive performance metrics in vertical farming environments. This represents a critical gap, as NASA-TLX and related workload tools are widely recognized for assessing multidimensional operator workload in human-system contexts (NASA, 2023). Failure to account for cognitive demands may therefore lead to incomplete or ineffective ergonomic interventions.

Future research should prioritize the integration of cognitive workload assessment with physical ergonomics evaluation, enabling a more comprehensive understanding of worker strain in VF systems. This should include subjective workload tools such as NASA-TLX, physiological or behavioral measures such as eye-tracking and pupil dilation, and performance-based indicators such as response time, error rate, and task accuracy (NASA, 2023; Yerebakan *et al*., 2025).

Environmental ergonomics in VF

While environmental factors such as temperature, humidity, lighting, and air quality are recognized as important ergonomic considerations, specific research on environmental ergonomics in vertical farming facilities is lacking. The unique environmental conditions created by high-density LED lighting, intensive climate control, and enclosed facility designs require systematic investigation to identify optimal environmental parameters that support both plant growth and worker health and comfort.

Socioeconomic and demographic factors

Research has identified demographic factors such as age, sex, and work experience as significant MSD risk modifiers (Yao *et al*., 2016; Bae *et al*., 2011). However, understanding of how these factors interact with VF-specific exposures remains limited. Additionally, socioeconomic dimensions including employment arrangements (permanent *vs* temporary workers), compensation structures (hourly *vs* piece-rate), and access to healthcare influence MSD outcomes but receive minimal attention in agricultural ergonomics literature. Research examining these

socioeconomic dimensions in VF contexts could inform more equitable and effective intervention strategies.

Economic analysis of interventions

While ergonomic interventions are often justified on humanitarian grounds, economic analysis demonstrating return on investment can facilitate implementation. Current literature provides limited economic evaluation of ergonomic interventions in agricultural contexts. Cost-benefit analyses examining intervention costs, productivity impacts, injury cost savings, and worker retention benefits would strengthen the business case for ergonomic investment in vertical farming operations.

Standardized assessment tools for VF

As previously discussed, existing ergonomic assessment tools may not fully capture VF-specific exposures and demands. Development and validation of standardized assessment tools specifically designed for vertical farming contexts represents a critical research need. Such tools should address multi-tier spatial configurations, human-automation interaction, cognitive demands, and the dynamic nature of VF work while maintaining practical feasibility for workplace application.

Underexplored ergonomic dimensions

Critical gaps exist in understanding manual handling exposure, access system design, visual ergonomics, anthropometric variability, and psychosocial risk factors in VF environments. These dimensions require targeted research to support comprehensive ergonomic assessment and intervention.

Future research directions

Longitudinal cohort studies

Establishing longitudinal cohorts of vertical farming workers represents a research priority. Such studies should track MSD incidence, symptom progression, and health outcomes over multiple years, enabling identification of critical exposure thresholds and high-risk subpopulations. Longitudinal designs also facilitate evaluation of intervention effectiveness over time, accounting for both immediate and long-term impacts. Ideally, cohort studies would incorporate multiple VF

facilities with varying designs, technologies, and work organization approaches to enable comparative analysis.

Human-automation interaction research

As VF automation advances, research must systematically examine human-automation interaction from ergonomic perspectives. Key research questions include:

- What is the optimal allocation of tasks between human workers and automated systems to minimize physical and cognitive workload while maintaining system performance?
- How should human-machine interfaces be designed to support effective monitoring, control, and intervention in automated VF systems?
- What are the cognitive demands of supervising and managing automated systems, and how can these demands be minimized through interface design and training?
- How does the introduction of automation affect job satisfaction, skill requirements, and employment patterns in VF operations?

Research should employ mixed methods, combining quantitative assessment of workload and performance with qualitative investigation of worker experiences and perceptions of automation.

8.3 Cognitive Ergonomics and Mental Workload Assessment

Comprehensive investigation of cognitive demands in vertical farming (VF) should move beyond conceptual discussion toward task-specific and measurable evaluation of mental workload. VF operations involve continuous system monitoring, interpretation of environmental and crop data, and coordination with automated technologies, all of which impose significant cognitive demands (Parasuraman *et al*., 2000; Wickens *et al*., 2015; Benos *et al*., 2023; Yerebakan and Hu, 2024).

Future research should explicitly assess:

- Mental workload associated with system monitoring, quality control, and decision-making tasks
- Attention and vigilance demands during prolonged monitoring activities
- Information processing requirements for interpreting sensor data and system alerts
- Cognitive fatigue and its interaction with physical fatigue under dual-task conditions

To address these demands, research should employ validated cognitive workload assessment methods. Subjective tools such as the NASA Task Load Index (NASA-TLX) enable multidimensional evaluation of perceived workload, while objective measures—including eye-

tracking, response time, error rates, and physiological indicators (e.g., heart rate variability, pupil dilation)—provide real-time assessment of cognitive strain (NASA, 2023; Carissoli *et al*., 2024). Integrating these methods with traditional physical ergonomics assessments will enable a holistic evaluation of total worker load, capturing the combined physical and cognitive demands characteristic of VF systems. Such integrated assessment is essential for informing human-centered design of interfaces, task allocation strategies, and training programs, ensuring that automation reduces overall workload rather than shifting burden from physical to cognitive domains (Benos *et al*., 2023; Legler, 2025).

Environmental ergonomics research

Systematic investigation of environmental factors in VF facilities should examine:

- Thermal comfort under various climate control configurations and LED lighting intensities
- Visual ergonomics of working under high-intensity LED lighting, including glare, color rendering, and flicker effects
- Air quality considerations in enclosed VF facilities, including CO2 levels, humidity, and potential accumulation of plant-derived aerosols
- Acoustic environment created by HVAC systems, pumps, and other equipment

Research should identify optimal environmental parameters that balance plant production requirements with worker comfort and health, potentially identifying design modifications that benefit both plants and people.

Participatory design research

Engaging VF workers in participatory design research can generate practical, acceptable solutions while building the evidence base for VF ergonomics. Participatory action research approaches should:

- Involve workers in identifying priority ergonomic concerns and constraints
- Co-develop and prototype intervention solutions with worker input
- Evaluate interventions through iterative testing and refinement
- Document the participatory process to inform best practices for worker engagement in VF system design

Participatory research is particularly valuable in the VF context given the novelty of these systems and the limited existing knowledge base regarding effective interventions.

Socioeconomic and policy research

Research examining socioeconomic dimensions of VF ergonomics should address:

- How employment arrangements (permanent *vs* temporary, full-time vs. part-time) influence MSD risk and access to interventions
- The impact of compensation structures (hourly *vs* piece-rate) on work pace, risk-taking behavior, and MSD outcomes
- Barriers to healthcare access and early intervention for MSD symptoms among VF workers
- Policy and regulatory frameworks that could support improved ergonomic conditions in VF operations

This research should employ mixed methods, combining quantitative epidemiological approaches with qualitative investigation of worker experiences and perspectives.

Sustainable automation strategies

Research should examine automation strategies that genuinely reduce worker burden while maintaining employment opportunities and job quality. Key questions include:

- Which tasks are most appropriate for automation from both technical feasibility and ergonomic benefit perspectives?
- How can automation be implemented to augment rather than replace human workers, creating safer and more satisfying jobs?
- What are the training and skill development requirements for workers in increasingly automated VF systems?
- How can automation be designed to be accessible and beneficial for workers with varying physical capabilities, including those with disabilities or age-related limitations?

This research should be informed by principles of sustainable work and decent work, ensuring that technological advancement supports rather than undermines worker well-being and employment quality.

Development of VF-specific assessment tools

Methodological research should focus on developing and validating assessment tools specifically designed for vertical farming contexts. Such tools should:

- Capture the unique postural demands of multi-tier systems
- Address both physical and cognitive workload dimensions
- Be practical for workplace application by VF operators without extensive ergonomics expertise
- Enable standardized assessment across different VF facilities and designs to support benchmarking and best practice identification

Tool development should follow rigorous validation procedures, including reliability testing, criterion validity assessment, and evaluation of sensitivity to detect ergonomic improvements following interventions.

Conclusions

Summary of key findings

This review synthesizes the currently available evidence relevant to ergonomics in vertical farming systems. While some findings derive from the small number of VF-specific studies, much of the present understanding is inferred from greenhouse and related controlled-environment agriculture contexts. Therefore, conclusions regarding VF-specific risk profiles and intervention priorities should be considered preliminary until validated through direct workplace research. Key findings include:

1. High MSD prevalence: agricultural workers, including those in greenhouse and indoor farming environments, experience alarmingly high rates of musculoskeletal disorders, with prevalence ranging from 50.9% to 89.3% across different populations (Farahbakhsh *et al*., 2025; Yao *et al*., 2016). The lower back, shoulders, knees, and neck emerge as the most commonly affected body regions.
2. Distinctive VF challenges: vertical farming introduces unique ergonomic challenges including multi-tiered spatial configurations requiring overhead reaching and awkward postures, repetitive precision tasks engaging multiple upper limb muscles, environmental factors related to controlled-environment conditions, and complex human-technology interactions (Lee *et al*., 2025; Kumar *et al*., 2023).

3. Assessment methodologies: Traditional ergonomic assessment tools (RULA, REBA, OWAS, OCRA) and advanced methods (EMG, physiological monitoring) have been applied in agricultural contexts, though their adaptation to vertical farming environments remains limited (Gómez-Galán *et al*., 2021; Nerona, 2023; Lee *et al*. 2025). Questionnaire-based approaches, particularly the Nordic Musculoskeletal Questionnaire, provide valuable epidemiological data (Farahbakhsh *et al*. 2025; Palmer, 1996).
4. Intervention strategies: Current interventions showing promise include workspace optimization to reduce extreme postures, tool redesign to minimize repetitive strain, automation of high-risk tasks, ergonomic furniture and support devices, participatory ergonomics approaches, and administrative controls (Kumar *et al*. 2023; Baron *et al*., 2001; Nerona, 2023; Lee *et al*., 2011). However, evidence of effectiveness varies, and VF-specific intervention research is minimal.
5. Critical knowledge gaps: Significant gaps persist regarding longitudinal health outcomes, human-automation interaction, cognitive ergonomics, environmental factors, socioeconomic dimensions, and economic analysis of interventions in VF contexts (Lee *et al*., 2025; Shamsipour *et al*., 2025). Collectively, these findings highlight the multidimensional and interacting nature of ergonomic risks in vertical farming, as conceptualized in the integrated framework presented earlier (Figure 3).

Collectively, these findings highlight the multidimensional and interacting nature of ergonomic risks in vertical farming, as conceptualized in the integrated framework presented earlier (Figure 3).

The imperative for human-centered design

As vertical farming technology and industry continue to advance, integrating human-centered design principles from the outset is essential. The history of agricultural mechanization demonstrates that technological innovation without adequate attention to human factors can create new occupational health challenges even while solving others (Kirkhorn *et al*., 2010). Vertical farming presents an opportunity to avoid repeating this pattern by proactively incorporating ergonomic considerations into system design, technology development, and operational practices. Human-centered design in VF requires:

- Anthropometric compatibility: designing tier spacing, access pathways, and workstations to accommodate human body dimensions and capabilities rather than requiring workers to adapt to systems optimized solely for plant production (ISO 2016)
- Task-technology fit: ensuring that automation and technology augment human capabilities and reduce burden rather than introducing new physical or cognitive demands
- Environmental optimization: balancing plant production requirements with worker comfort and health in environmental control strategies
- Participatory approaches: engaging workers in system design and continuous improvement processes to leverage their expertise and ensure practical, acceptable solutions
- Comprehensive assessment: evaluating both physical and cognitive demands, short-term and long-term health outcomes, and individual and organizational factors that influence worker well-being

Implications for practice

For vertical farming operators, this review highlights several practical implications:

1. Proactive ergonomic assessment: conduct systematic ergonomic assessments of VF operations using appropriate tools (RULA, REBA, questionnaires) to identify high-risk tasks and exposures before injuries occur.
2. Multi-faceted interventions: implement comprehensive intervention strategies addressing engineering controls (workspace design, tool modification), administrative controls (work organization, training), and participatory approaches rather than relying on single interventions.
3. Worker engagement: involve workers in identifying ergonomic concerns and developing solutions, leveraging their practical knowledge and increasing intervention acceptance.
4. Monitoring and evaluation: establish systems for ongoing monitoring of MSD symptoms, injury rates, and intervention effectiveness to enable continuous improvement.
5. Automation with caution: approach automation strategically, carefully evaluating the ergonomic implications of human-automation interaction and ensuring that automation genuinely reduces rather than transforms worker burden.

Implications for policy and regulation

The emerging vertical farming industry operates in a regulatory environment largely developed for conventional agriculture or industrial workplaces. Policymakers should consider:

- Developing VF-specific occupational health and safety guidelines that address the unique characteristics of these systems
- Requiring ergonomic assessment and intervention planning as part of VF facility design and operation
- Supporting research on VF ergonomics through targeted funding programs
- Facilitating information sharing and best practice dissemination across the VF industry
- Ensuring that labor standards and worker protections apply equally to VF operations as to other agricultural and industrial sectors

Final perspective

Vertical farming holds tremendous promise for addressing global food security, environmental sustainability, and urban agriculture challenges. Realizing this promise requires not only technological innovation in plant science, engineering, and automation, but also sustained attention to the human dimension of these systems. Workers are not simply components to be accommodated within VF systems; they are skilled professionals whose health, safety, and well-being are both ethical imperatives and practical necessities for operational success.

Vertical farming offers substantial opportunities for sustainable food production, but realizing this potential requires stronger evidence regarding worker health and system design. Future studies conducted directly within commercial VF environments are essential to determine whether currently hypothesized ergonomic risks and solutions are borne out in practice.

Limitations of the review

This review has several limitations that should be considered when interpreting its findings.

First, the most significant limitation is the scarcity of ergonomics research conducted directly in vertical farming (VF) environments. As a result, much of the evidence synthesized in this review is derived from greenhouse and broader controlled-environment agriculture (CEA) systems. While these systems share certain characteristics with VF, important differences in spatial configuration, automation, and task design limit the direct transferability of findings.

Second, the included studies exhibit substantial heterogeneity in study design, populations, tasks, and assessment methodologies, which limits the ability to draw consistent or quantitative conclusions. The predominance of cross-sectional studies further restricts causal inference and understanding of long-term health outcomes.

Third, the review relies primarily on observational and descriptive studies, with relatively few intervention-based or longitudinal investigations available. This limits the strength of evidence regarding the effectiveness of ergonomic interventions in VF contexts.

Fourth, potential publication bias and language restrictions (English-only studies) may have influenced the body of literature included.

Finally, given the emerging nature of VF systems, many conclusions presented in this review—particularly those related to VF-specific risks—should be interpreted as preliminary and hypothesis-generating, rather than definitive.

Future research conducted directly within commercial VF environments is essential to validate and refine the findings presented in this review.

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Table 1. Summary of included studies by theme.

Theme	Focus of studies	Key findings / evidence	Representative sources (as cited in manuscript)
Musculoskeletal disorders (MSDS) in agriculture & CEA	Prevalence, affected body regions, risk factors	High MSD prevalence (50.9%–89.3%); lower back, shoulders, knees, neck most affected; driven by repetitive motion, awkward postures, forceful exertion	Yao *et al*. (2016); Farahbakhsh *et al*. (2025); Benos *et al*. (2020); Punnett & Wegman (2004)
Greenhouse & controlled-environment ergonomics	Task-related risks in greenhouse systems	Prolonged bending, lifting, repetitive upper limb tasks; specific disorders (e.g., "tomato trainer's shoulder"); high repetition (10,000–16,000/week)	Palmer (1996); Gómez-Galán *et al*. (2021); Kim *et al*. (2023)
Vertical farming ergonomic challenges	Unique VF system characteristics	Multi-tier systems → overhead reaching & stooping; precision tasks; environmental stressors; human–machine interaction; increased cognitive load	Lee *et al*. (2025); Kumar *et al*. (2023); Kirkhorn *et al*. (2010)
Postural & biomechanical risk assessment	Observational tools (RULA, REBA, OWAS, OCRA)	High-risk postures frequently identified; RULA levels 3–4 common; REBA scores indicate high risk; OCRA shows unacceptable repetition exposure	Gómez-Galán *et al*. (2021); Nerona (2023); Cecchini *et al*. (2010)
Physiological & EMG-based assessment	Objective workload measurement	Increased heart rate, oxygen consumption with height/reach; EMG shows high activation in anterior deltoid and forearm muscles during VF tasks	Kumar *et al*. (2023); Lee *et al*. (2025); Mirka *et al*. (2003)
Questionnaire & survey methods	Self-reported MSD prevalence	Nordic Musculoskeletal Questionnaire widely used; enables cross-study comparison; identifies task-specific symptom patterns	Yao *et al*. (2016); Farahbakhsh *et al*. (2025); Palmer (1996)
Engineering & workspace interventions	Design modifications to reduce strain	Adjustable platforms, optimized reach distances, redesigned workstations reduce physiological load and awkward postures	Kumar *et al*. (2023); Baron *et al*. (2001); ISO (2016)
Tool design & assistive technologies	Ergonomic tool improvements	Modified tools reduce grip force, repetition, and strain (e.g., electric scissors, berry rakes, lighter containers)	Baron *et al*. (2001); Lee *et al*. (2011)
Automation & mechanization	Replacement or support of manual tasks	Optical sorters and mechanized systems reduce repetitive strain; risk of shifting burden to cognitive workload	Cecchini *et al*. (2010); Lee *et al*. (2011); Parasuraman *et al*. (2000)

Theme	Focus of studies	Key findings / evidence	Representative sources (as cited in manuscript)
Ergonomic furniture & supports	Posture-supporting devices	Adjustable chairs and supports reduce REBA scores and improve posture during prolonged tasks	Nerona (2023)
Participatory ergonomics	Worker involvement in solutions	Worker-inclusive interventions reduce injuries (>50%) and improve adoption of solutions	Baron *et al*. (2001); Kee (2022)
Administrative controls	Work organization strategies	Task rotation, work-rest cycles, training reduce cumulative exposure and MSD risk	Yao *et al*. (2016); Lee *et al*. (2011)
Knowledge gaps in VF ergonomics	Research limitations	Lack of VF-specific studies, longitudinal data, cognitive ergonomics, human-automation interaction, environmental ergonomics	Lee *et al*. (2025); Shamsipour *et al*. (2025); Kirkhorn *et al*. (2010)

Table 2. Cognitive demands associated with common vertical farming tasks.

VF Task	Primary cognitive demands	Potential ergonomic implications
System monitoring	Sustained attention, vigilance, interpretation of sensor data, response to alarms	Mental fatigue, reduced situational awareness, delayed response to system failures
Harvesting	Selective decision-making, quality judgement, visual discrimination, coordination across tiers	Dual-task interference when combined with reaching, repetition, or awkward postures
Transplanting and seeding	Sequencing, accuracy checking, attention to spacing and plant condition	Increased error risk under time pressure or repetitive work conditions
Quality inspection and grading	Visual scanning, defect detection, rapid classification, sustained concentration	Eye strain, cognitive fatigue, reduced inspection accuracy over time
Nutrient and climate management	Interpretation of environmental data, troubleshooting, adjustment of control systems	High decision-making demand, potential stress during system deviations
Equipment maintenance and troubleshooting	Diagnosis of faults, procedural memory, safety awareness, coordination with automated systems	Increased cognitive load, error risk, and safety concerns during non-routine tasks
Human–machine interaction	Interface navigation, alarm prioritization, system override decisions, monitoring automation	Automation-related workload, overreliance, alert fatigue, or loss of manual skill

Table 3. Task-based ergonomic risks in vertical farming.

Task	Typical activities	Key risk factors	Affected body regions
Seeding & propagation	Tray filling, sowing seeds	Repetition, fine motor strain, static sitting/standing	Wrist, fingers, neck
Transplanting	Moving seedlings to grow trays	Bending, reaching, light lifting	Lower back, shoulders
Crop maintenance	Pruning, training, adjusting plants	Repetition, overhead work	Shoulders, neck
Harvesting	Cutting, picking, carrying trays	Repetition, awkward postures, load handling	Wrist, shoulders, back
Monitoring & inspection	Visual inspection, data logging	Static posture, visual strain, cognitive load	Neck, eyes
System maintenance	Cleaning, repairs, equipment adjustment	Forceful exertion, awkward postures	Back, knees, hands

Table 4. Conceptual comparison of worker demands across agricultural production systems (field, greenhouse CEA, and vertical farming), based on available literature and inferred VF characteristics.

Topic	Direct VF evidence	Greenhouse/CEA evidence	Strength
Muscle activation	Yes	Limited	Moderate
MSD prevalence	No	Yes	Indirect
Overhead work risk	Limited	Yes	Indirect
Human-automation interaction	Minimal	Minimal	Low

Vertical farming is considered a subset of indoor farming within the broader CEA framework; values for VF reflect limited direct evidence and conceptual inference.