Ornamental Horticulture
ISSN 2447-536X | WWW.ORNAMENTALHORTICULTURE.COM.BR
SBFPO Sociedade Brasileira de Floricultura e Plantas Ornamentais

Review Article

Advances and evidence gaps in Colombian Floriculture (2020-2026): Production, technology, and sustainability

Avanços e lacunas do conhecimento na Floricultura Colombiana (2020-2026): Produção, tecnologia e sustentabilidade

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Abstract
Colombian floriculture faces interacting constraints in crop protection, greenhouse climate, nutrition, postharvest operations and sustainability. This review maps research published from 2020 to 2026 and critically evaluates the conditions under which its findings can support commercial decisions. A Scopus-derived export of 89 unique records yielded 49 publications for the main evidence map, 4 contextual sources and 36 out-of-scope records. Publications were classified into six thematic domains and interpreted according to study design, experimental setting, comparators, validation and outcome boundaries. Detailed report-level appraisal covered 46 publications; 3 records contributed descriptive evidence. Crop protection accounted for 17 publications, followed by digitalization and processes (eight), microclimate and phenology (seven), work and socioeconomic dimensions (seven), nutrition (five), and environmental sustainability (five). The evidence documents spatial climate heterogeneity in passive greenhouses, cultivar-specific thermal requirements, resistance to selected fungicides, alternative protection treatments, stage-dependent spectral diagnosis and improvements in defined mechanical processes. Environmental assessments identify input-related burdens and evaluate cleaner-production scenarios, while occupational studies reveal work-related constraints that are seldom integrated into technological assessments. Reported benefits remain conditional on the cultivar, site, exposure period, comparator and system boundary. Model performance, laboratory efficacy and scenario estimates therefore cannot be interpreted as equivalent measures of commercial effectiveness. Priority research should connect microclimate, plant response, phytosanitary pressure, flower quality, resource flows and worker outcomes within replicated production trials and independently validated decision systems.
Keywords: Cut flowers, life cycle assessment, protected cultivation, phytosanitary management, precision agriculture.

Resumo
A floricultura colombiana enfrenta limitações interligadas na proteção fitossanitária, no microclima, na nutrição, na pós-colheita e na sustentabilidade. Esta revisão mapeia pesquisas publicadas entre 2020 e 2026 e avalia criticamente as condições em que seus resultados podem apoiar decisões comerciais. Uma base derivada da Scopus com 89 registros únicos resultou em 49 publicações no mapa principal, 4 fontes contextuais e 36 registros fora do escopo. As publicações foram organizadas em seis eixos e interpretadas segundo o delineamento, as condições experimentais, os comparadores, a validação e os limites dos indicadores. A avaliação detalhada abrangeu 46 publicações; 3 registros contribuíram com evidência descritiva. A proteção fitossanitária reuniu 17 publicações, seguida de digitalização e processos (oito), microclima e fenologia (sete), trabalho e aspectos socioeconômicos (sete), nutrição (cinco) e sustentabilidade ambiental (cinco). Os estudos documentam heterogeneidade microclimática em estufas passivas, exigências térmicas específicas por cultivar, resistência a determinados fungicidas, tratamentos alternativos, diagnóstico espectral dependente do estágio fenológico e melhorias em processos mecânicos definidos. As avaliações ambientais identificam impactos associados aos insumos e examinam cenários de produção mais limpa. Os estudos ocupacionais mostram limitações raramente integradas às avaliações tecnológicas. Os benefícios dependem da cultivar, do local, do período de exposição, do comparador e dos limites do sistema. O desempenho preditivo, a eficácia laboratorial e as estimativas de cenários não representam medidas equivalentes de efetividade comercial. As prioridades são ensaios integrados que relacionem microclima, resposta vegetal, sanidade, qualidade floral, recursos e condições de trabalho, com validação independente.
Palavras-chave: Agricultura de precisão, avaliação do ciclo de vida, cultivo protegido, flores de corte, manejo fitossanitário.

Introduction

Commercial cut-flower production combines biological management with strict requirements for harvest timing, stem quality, phytosanitary status and postharvest performance. In Colombia, these requirements extend from the greenhouse to export markets and depend on operations performed by a large and specialized workforce. Research has consequently addressed a diverse set of problems, including pest interception in hydrangea consignments, international competitiveness and working conditions. These studies identify constraints at different scales: a treatment may improve a plant or process response without resolving limitations in logistics, occupational conditions or environmental performance (Molina-Acosta et al., 2021; Hernández-Bello et al., 2022; Avendaño Ruiz et al., 2023). A review that connects these scales can clarify which findings support a management decision and which still require validation.

Crop protection remains central because disease symptoms, arthropod presence and treatment damage can directly affect the commercial acceptability of flowers. Research on Colombian production systems has characterized predatory mites and thrips, differentiated fungal causes of carnation rot, and assessed fungicide resistance in rose-associated *Botrytis cinerea*. Biological agents, ultraviolet treatments and induced plant resistance offer additional mechanisms for protection, but their performance depends on the organism, dose, exposure conditions and response measured (Vega et al., 2020; Rueda-Ramírez et al., 2021; Filgueira Duarte et al., 2022; Giraldo et al., 2024). This diversity makes comparison useful only when intervention efficacy is retained alongside its experimental context and effects on flower quality.

The greenhouse environment also conditions plant development and phytosanitary processes. Measurements in passive structures reveal substantial spatial variation in air temperature, relative humidity and vapor pressure deficit (VPD). Computational fluid dynamics (CFD) helps explain airflow and thermal distributions, while phenological models describe cultivar-specific development through accumulated thermal time (Villagrán and Bojacá, 2020a, 2020b; Villagrán et al., 2021, 2022; Buitrago-Rueda et al., 2025). These approaches are complementary, but a successful prediction of greenhouse temperature does not establish the

***Corresponding author:** evillagran@agrosavia.co | https://doi.org/10.1590/2447-536X.v32.e3134 | Editor: Patrícia Duarte de Oliveira Paiva, Universidade Federal de Lavras, Brasil | Received: Oct 08, 2026 | Accepted: Nov 10, 2026 | Available online: Nov 23, 2026 | Licensed by CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/)

accuracy of a harvest forecast or a disease-control decision. Integrating the approaches requires observations that connect environmental exposure with physiological and commercial outcomes.

Nutrient diagnosis, drainage recirculation and digital monitoring introduce further opportunities and trade-offs. Corrective fertilization can improve mineral balance and stem characteristics, whereas recirculation may increase concentrations of poorly absorbed ions. Spectral and image-based models can support diagnosis and phenological monitoring, although their applicability depends on crop stage and the independence of validation data (Franco-Hermida et al., 2020; Vélez Carvajal et al., 2023; Cuervo-Bejarano et al., 2025; Franco Montoya and Martínez Martínez, 2025a). Similarly, life-cycle assessments and ergonomic studies measure different dimensions of sustainability. Environmental impact scenarios, worker symptoms and process productivity should inform a common decision without being combined into an unsupported overall benefit (Arenas et al., 2024a, 2024b; González et al., 2024).

The objective of this review is to map and critically synthesize research on Colombian floriculture published during 2020–2026, distinguishing demonstrated outcomes from proposed applications. Four questions guide the analysis: Which production and sustainability domains are represented? What evidence supports the reported technological and management advances? How do study design, validation and system boundaries affect their transferability? Which gaps constrain the integration of crop protection, microclimate, nutrition, operations and sustainability in commercial production? The synthesis retains the heterogeneity of the evidence and identifies the measurements and comparisons needed for stronger operational conclusions.

Materials and methods

Review design and scope

A systematic evidence review and critical narrative synthesis were developed to examine scientific advances in Colombian floriculture during the 2020–2026 period. The review was organized according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) reporting framework (Page et al., 2021), with particular emphasis on methodological transparency, reproducibility, and the interpretation of evidence across heterogeneous research designs.

The review addressed six interconnected research domains: (i) crop protection and phytosanitary management; (ii) greenhouse microclimate, crop phenology, and modeling; (iii) mineral nutrition, substrates, and productive management; (iv) digital technologies, automation, and process optimization; (v) environmental and territorial sustainability; and (vi) occupational health, ergonomics, and socioeconomic performance. The unit of analysis was the individual publication, acknowledging that different publications could report related experiments or research activities.

Given the diversity of experimental designs, interventions, study populations, and response variables, quantitative meta-analysis was considered inappropriate. Instead, a structured narrative approach was adopted to compare documented results, assess the strength and limitations of the available evidence, and identify technological and scientific gaps relevant to Colombian floriculture.

Information source and search strategy

The bibliographic search was conducted on August 2, 2026using Scopus as the scientific literature database. The search covered publications dated from 2020 to 2026 and was applied to the title, abstract, and keyword fields through the TITLE-ABS-KEY operator. The strategy combined terminology describing floriculture, cut flowers, ornamental production, and commercially relevant floral crops with geographic descriptors identifying research associated with Colombia. The search expression was formulated as follows:

TITLE-ABS-KEY(floricultur* OR “flower production” OR “cut flower*” OR “ornamental plant*” OR “ornamental crop*” OR “flower cultivation” OR “ornamental horticulture” OR “protected floriculture” OR “greenhouse flower" OR rose* OR carnation* OR chrysanthemum* OR alstroemeria* OR hydrangea* OR gerbera* OR orchid* OR “Gypsophila” OR “Dianthus caryophyllus” OR “Rosa hybrida” OR “Chrysanthemum” OR “Alstroemeria” OR “Hydrangea”) AND TITLE-ABS-KEY(Colombia OR Colombian) AND PUBYEAR > 2019 AND PUBYEAR < 2027.

The search strategy was intended to capture the multidisciplinary nature of Colombian floriculture research, including studies in which the principal scientific contribution concerned plant physiology, engineering, environmental assessment, computational modeling, or socioeconomic conditions rather than floriculture as a general sectoral category. The preserved bibliographic dataset comprised 89 Scopus records within the defined publication window. The exported metadata included publication title, authors, year, source title, digital object identifier (DOI), Scopus identifier, document type, keywords, and abstract.

Eligibility criteria and study selection

Studies were considered eligible when they provided direct scientific evidence concerning Colombian cut-flower or ornamental production, including cultivation practices, crop protection, plant nutrition, greenhouse microclimate, postharvest management, technological development, and the environmental, occupational, or socioeconomic dimensions of floriculture. Multinational investigations were retained when they reported identifiable information concerning Colombian floriculture. Publication year, rather than the year of experimental data collection, determined eligibility within the 2020–2026 period. Journal articles, conference papers, and book chapters were evaluated according to their relevance to the research questions and their contribution to the available evidence. Publications combining secondary literature synthesis with original empirical investigations were considered only for their independently reported primary findings, avoiding the double counting of evidence from previously published studies.

Records addressing unrelated agricultural systems, environmental or health issues without a demonstrable connection to Colombian floriculture, or only incidental references to ornamental production were excluded. Broader regional and multisectoral publications providing useful interpretative information, but without a sufficiently direct focus on Colombian floriculture, were classified separately as contextual sources. Bibliographic records were audited using digital object identifiers (DOIs), Scopus identifiers, and normalized publication titles to identify potential duplicates and verify bibliographic consistency. The resulting selection comprised 49 publications retained for the principal evidence synthesis, four publications classified as contextual support, and 36 records excluded from the analytical corpus. The documented identification and selection outcomes are summarized in the PRISMA 2020-based flow diagram (Fig. 1). The selection decisions for the preserved 89-record Scopus export are documented in Supplementary Table S2 (https://doi.org/10.6084/m9.figshare.34969819), including bibliographic identifiers, thematic classifications, and reasons for exclusion or contextual classification.

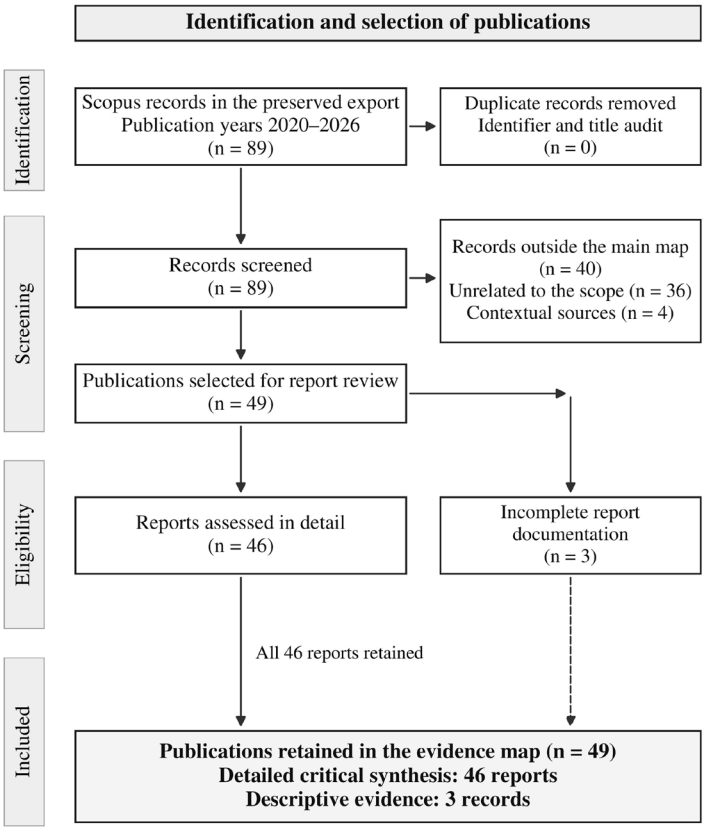


Fig. 1. PRISMA 2020-adapted flow diagram for the preserved Scopus export.

Data extraction and thematic classification

Information from the selected publications was organized in a structured evidence matrix that included bibliographic information, study characteristics, principal findings, and reported limitations. The analysis focused on identifying relevant scientific contributions, comparing research approaches, and examining the applicability of the reported results to Colombian floriculture. The extracted information provided the basis for the thematic classification and critical synthesis of the available evidence.

Attention was given to the interpretation of the reported outcomes within their original experimental or analytical boundaries. Numerical results were documented with their corresponding units, comparators, observation periods, and statistical significance when available. Experimentally measured outcomes were distinguished from simulation-based estimates, while statistical associations were interpreted separately from demonstrated causal relationships. When results were not reported or could not be established from the available evidence, no values were inferred.

Each publication was assigned to one predominant thematic category for descriptive analysis: (i) crop protection and phytosanitary management; (ii) greenhouse microclimate, phenology, and modeling; (iii) nutrition, substrates, and productive management; (iv) digitalization, automation, and process optimization; (v) environmental and territorial sustainability; and (vi) occupational health, ergonomics, and socioeconomic performance. Publications addressing multiple research domains were additionally examined for their contribution to cross-disciplinary relationships. The publication-level extraction matrix, including the principal findings, methodological characteristics, limitations, and scope of evidence assessment, is presented in Supplementary Table S1 (https://doi.org/10.6084/m9.figshare.34969819). This supplementary material provides the analytical basis for verifying the findings discussed in the manuscript and distinguishing directly supported results from broader technological implications.

Methodological appraisal and critical evidence synthesis

The methodological appraisal was adapted to the diversity of research designs represented in the selected publications. Experimental investigations were examined according to their experimental units, replication, treatment structure, controls, response measurements, and reported statistical analyses. Observational studies were considered in relation to sampling coverage, measurement protocols, potential confounding factors, and the limitations of causal interpretation. Computational and predictive investigations were examined in terms of model assumptions, calibration procedures, validation strategies, reported performance metrics, and evidence supporting their application beyond the original experimental conditions. Attention was given to whether model performance was evaluated using independent observations and whether transferability across cultivars, production environments, locations, or growing seasons was demonstrated.

Environmental life-cycle assessments were interpreted considering their functional units, system boundaries, inventory assumptions, impact assessment methods, and evaluated improvement scenarios. Occupational, ergonomic, and socioeconomic investigations were assessed according to their study populations, data collection methods, analytical approaches, and the scope of inference supported by their findings. The methodological characteristics and principal limitations identified for each publication were recorded in Supplementary Table S1 (https://doi.org/10.6084/m9.figshare.34969819). These criteria guided the interpretation of the evidence without imposing a single numerical quality score across fundamentally different study designs.

A critical narrative synthesis was developed by comparing results within methodologically compatible groups before examining relationships across research domains. The synthesis distinguished experimentally validated interventions from technological proposals, predictive associations from observed biological responses, and modeled environmental benefits from measured operational improvements. Attention was given to the consistency of results, experimental and geographical representativeness, and the maturity of the evidence supporting potential commercial applications. Research gaps were identified through recurring limitations in experimental validation, restricted cultivar or geographical coverage, insufficient longitudinal assessment, and limited integration among greenhouse microclimate, crop physiology, phytosanitary management, technological systems,

and sustainability indicators. These findings provided the foundation for evaluating the progression of Colombian floriculture research from environmental and biological characterization toward predictive management and integrated production systems.

Results and discussion

Composition of the evidence base

The 49-publication evidence map comprises 41 journal articles, four conference papers, three book chapters and one review with original survey data, according to the source export. Annual counts were five in 2020, nine in 2021, seven in 2022, five in 2023, twelve in 2024, nine in 2025 and two in 2026. These values characterize the retained corpus rather than national research output. Crop protection was the largest domain; the remaining publications distributed research effort across greenhouse engineering, plant nutrition, digital operations, environmental performance and work-related questions (Table 1). The presence of several designs within a domain makes publication frequency a measure of coverage, not of evidence strength.

Table 1. Distribution of publications by predominant thematic domain.

Domain	n	(%)	Main scope
Crop protection	17	34.7	Pathogens, arthropods, resistance and treatments
Digitalization and processes	8	16.3	Optical diagnosis, machine vision and operations
Microclimate and phenology	7	14.3	Climate heterogeneity, CFD and growth models
Work and socioeconomic dimensions	7	14.3	Ergonomics, worker outcomes and competitiveness
Nutrition and productive management	5	10.2	Nutrient diagnosis, substrates and recirculation
Environmental and territorial sustainability	5	10.2	Life-cycle assessment, effluents and habitats
Total	49	100.0	One category per publication

Percentages use 49 publications as the denominator and may differ from 100% when rounded individually. The four contextual sources are not included. n: number of publications, CFD: computational fluid dynamics.

Crop protection and phytosanitary management

Crop-health studies cover both causal diagnosis and management interventions. In carnation, the identification of *Fusarium verticillioides* as an additional cause of basal rot expands the etiological basis for differentiating vascular and basal symptoms; the sampled population also contained *F. oxysporum* and mixed detections (Filgueira Duarte et al., 2022). In rose, surveys of Mesostigmata and thrips identified potentially beneficial soil predator assemblages and their associations with organic matter and seminatural vegetation, but abundance correlations should not be interpreted as field-level pest-suppression efficacy (Rueda-Ramírez et al., 2021). Monitoring of *Frankliniella occidentalis* in chrysanthemum showed that plant-level sampling methodology can materially alter observed pest counts, establishing a practical source of surveillance bias (Silva-Castaño and Brochero, 2021). Complementary hydrangea packing-house inspections showed that postharvest interceptions depend on sampling context and management characteristics rather than a stable cultivar-specific pest signature (Molina-Acosta et al., 2021).

Evidence on chemical control also requires treatment-specific interpretation. A Colombian isolate survey detected marked differences among *Botrytis cinerea* isolates in susceptibility to fenhexamid, carboxin and prochloraz, including moderate-to-high carboxin resistance in a large fraction of the analyzed isolates (Giraldo et al., 2024). Laboratory tests against *Trialeurodes vaporariorum* similarly produced widely different median lethal concentrations among insecticides, but toxicological rankings cannot substitute for evaluation of beneficial organisms, resistance evolution or field application (Belalcázar-Mejía et al., 2026). In export-oriented postharvest treatment, phosphine reached high thrips mortality after a 24 h exposure under the reported protocol, while a botanical extract did not significantly improve the outcome; the observed efficacy was specific to the evaluated disinfestation protocol and cannot be extrapolated to other pest species or shipping conditions (Lizarazo-Peña et al., 2024).

Biological control, semiochemical attraction, and acoustic deterrence represent distinct pest-management strategies. Fermentation-produced *Akanthomyces lecanii* showed encouraging control of *Tetranychus urticae* in gerbera, but laboratory immobility, field treatment response and industrial inoculum productivity are distinct endpoints (Medina et al., 2021). *Orius insidiosus* responded to volatile compounds involved in rose–thrips interactions, with functional-response changes suggesting a route toward semiochemical-assisted biological control; plot-scale attraction alone does not yet establish farm-level suppression (Díaz et al., 2025). A device imitating bat-frequency emissions against *Copitarsia decolora* provides a preliminary behavioral approach, but quantitative field efficacy and repeatability were not established to the level needed for routine recommendation (Penagos et al., 2025).

A notably coherent body of carnation research examines *Fusarium oxysporum* f. sp. dianthi (Fod) infection across physiology, induced resistance and molecular response. In susceptible material, leaf warming and photosynthetic impairment preceded or accompanied visible disease development; comparison of resistant Golem and susceptible Mizuky subsequently implicated cultivar-dependent stomatal responses and abscisic acid (ABA) and salicylic acid (SA) signaling (Bustos-Caro et al., 2024a, 2024b). Exogenous thiamine decreased wilt severity under experimental conditions, while proteomic analysis documented changes in defense-, redox- and signaling-associated proteins after treatment and challenge (Pérez Mora et al., 2024a, 2024b). These results progress from symptom characterization toward mechanistic hypotheses, but neither a leaf-temperature threshold nor a reproducible predictive classifier was demonstrated for diverse field environments. Potential overlaps in experimental material or datasets among related publications must be considered when assessing the independence of the reported findings.

Controlled ultraviolet-C (UV-C) treatment reduced Botrytis conidial germination under a defined postharvest protocol (Vega et al., 2020). Disease control and phototoxicity must nevertheless be considered together, and transport conditions or vase life cannot be inferred from germination alone. RGB analysis of rose leaflets also distinguished lesion-associated image characteristics under laboratory conditions (Cuervo-Bejarano and Lopez-Espinosa, 2021). The study identified lesion-associated image features, although the available methodological information was insufficient to fully assess classification performance. Across these approaches, the practical gap is the conversion of an experimentally discriminating response into a treatment or diagnostic rule that remains reliable across cultivars, disease pressure and commercial handling.

Greenhouse microclimate and cultivar development

In commercial Colombian rose and carnation greenhouses, sensor-grid analyses documented strong spatial gradients in temperature, relative humidity and VPD, including daytime thermal differences of about 6-7 °C and relative-humidity differences exceeding 30 percentage points under the reported radiation regimes (Villagrán and Bojacá, 2020a, 2020b). Multistructure geostatistical comparisons suggest that configuration and radiation load jointly govern this heterogeneity (Villagrán et al., 2022). CFD simulations provide mechanisms consistent with this empirical pattern: inadequate exchange under selected wind conditions, thermal stagnation zones and sensitivity to outside wind (Villagrán et al., 2021). The agreement is qualitative across distinct buildings, not a pooled climate-response magnitude.

From an agronomic perspective, regional averages or a single greenhouse air sensor are insufficient proxies for plant-level exposure. However, the surveyed studies rarely link spatially resolved microclimate

to measured stem grade, canopy physiological measurements and pathogen dynamics within the same experiment. The available data do not quantify the effect of a 6 °C temperature gradient on commercial stem quality. The reported temperature and humidity distributions instead justify testable management hypotheses about ventilation redesign, zonal monitoring and coupled crop-response experiments (Villagrán and Bojacá, 2020a, 2020b; Villagrán et al., 2021, 2022).

Phenological models constitute an important biological complement to climate characterization. Carnation studies associated bud development and harvest timing with accumulated growing degree-days (GDD), revealing substantial cultivar differences: Ilusion required more accumulated thermal time than Moon Light over the analyzed bud-development interval, while Mizuky and Zafiro differed in stage-specific base temperatures despite similar overall thermal demands (Leguízamo-Medina et al., 2022; Buitrago-Rueda et al., 2025). In rose, Freedom, Pink Floyd and Mondial differed in GDD accumulation and the timing of marketable floral stages; growth-curve analysis also showed that the appropriate sigmoid form can depend on the organ and cultivar (Álvarez-Herrera et al., 2025). These models are promising tools for crop scheduling, yet cultivar-specific parameters and differences in the developmental window or base-temperature definition prevent direct pooling of reported GDD values across studies.

The distinction between model validation and management validation is particularly relevant here. The CFD study evaluated predicted temperature and air velocity against observations, whereas phenological studies fitted development to cultivar-specific thermal exposure. Both contribute useful evidence within their validation domain. A stronger integrated test would couple the spatial exposure experienced by marked stems with their phenological progression, harvest quality and disease occurrence. Such a design would help determine whether ventilation improvements alter commercially meaningful outcomes rather than only air-temperature distributions.

Nutrient diagnosis and drainage recirculation

In greenhouse rose production, the Diagnosis and Recommendation Integrated System (DRIS) and Compositional Nutrient Diagnosis (CND) attempted to interpret mineral balance relative to plant performance rather than consider each nutrient independently. Intervention-oriented validation reported improvements in commercially relevant stem characteristics in a defined cycle, without a universal increase in total yield (Franco-Hermida et al., 2020). Related work showed that silicon supply in hydroponic rose 'Snowflake' changed mineral concentrations (including Ca, Mg, S, Mn, B and Zn), while N, P and K remained statistically unresponsive in the evaluated treatments (Guio Rodríguez et al., 2022).

In a cultivar-specific rose experiment, exogenous ascorbic acid increased selected measures of stem length and diameter, but responses in flower-head dimensions and chlorophyll were not uniformly beneficial across cultivars (Casierra-Posada et al., 2022). Responses to ascorbic acid therefore varied according to cultivar and the measured plant characteristic.

Spectral diagnosis extends conventional chemical analysis, but the strongest reported performance depends on phenological stage. The rose manganese studies related visible and near-infrared (VIS-NIR) reflectance to tissue concentration and subsequently compared multivariate prediction models (Franco Montoya and Martínez Martínez, 2024, 2025a). The models were evaluated using separate validation observations, with lower predictive performance during early phenological stages. Their applicability across farms, cultivars and production environments remains to be established. A commercial diagnostic protocol would need to specify the sampling stage, reference laboratory procedure and decision threshold for fertilizer adjustment.

The environmental case for recirculation also contains agronomic trade-offs. Carnation experiments contrasting drainage recycling intensities and substrates documented shifts in nutrient concentrations in recycled solution, while a rose study identified the tendency for sodium and chloride accumulation under higher recirculation (Vélez Carvajal et al., 2023; Cuervo-Bejarano et al., 2025). Increased recovery of drainage does not establish simultaneous optimization of salinity, nutrient uptake, yield and water footprint. Comparative follow-up should explicitly measure reclaimed water fraction, substrate solution chemistry, plant response, discharge volume and operational control under identical system boundaries.

Digital systems and mechanical processes

Spectral experiments, RGB imaging and deep-learning studies address different diagnostic and monitoring tasks and require distinct validation strategies. Early chrysanthemum multispectral imaging described symptom-sensitive wavelength combinations without robust independent diagnostic classification metrics (Sánchez-Ríos et al., 2020). Later rose-image studies trained YOLOv8 models to recognize phenological stages using commercially acquired RGB imagery; the best-developed class achieved an F1 score around 0.84 in testing, whereas discrimination of early or smaller objects remained weaker (Franco Montoya et al., 2025b). Such findings show the feasibility of image-based phenotyping, not that an autonomous scouting solution has been implemented and maintained across farms.

Operational studies differed in whether improvements were estimated through simulation or measured after physical modifications. Business process management (BPM) analyses describe workflow and inventory bottlenecks; their simulation results should be interpreted as opportunities for redesign rather than measured production gains (Rodríguez et al., 2021a; Lozano-Gil et al., 2023). In contrast, a carnation machinery study reported a reduction in damaged stems after physical modification, although the evidence derives from one industrial case (Cuenca Orozco et al., 2024). The reported computational reduction in optimization time concerns the search algorithm, not a reduction of the same magnitude in factory energy or labor demand.

Meteorological regression was also used to estimate pest and disease incidence in roses (Lombana-Peña et al., 2023). Reported agreement with observed incidence demonstrates an association within the evaluated dataset. Prospective forecasting would additionally require an explicit prediction horizon, temporal separation of training and test data, and comparison with a practical baseline. Because weather, crop stage and crop protection practices can change together, a fitted relationship cannot establish which management action will prevent a future outbreak. Linking predicted risk to the outcome of a pre-specified intervention is therefore a separate validation task.

Mantilla et al. (2025) combined literature synthesis with responses from 18 large enterprises operating in Colombia and Ecuador, identifying greater reported use of IoT/wireless sensor networks than advanced robotics or machine learning. This was a two-country convenience survey rather than a representative Colombian adoption census. The survey suggests differences in technology adoption among the participating enterprises but does not provide representative adoption rates for Colombia.

Table 2 summarizes selected quantitative findings and identifies the experimental conditions, comparison criteria, and measurement scales that delimit their interpretation. For example, a class-specific F1 score, a spatial temperature difference and a modeled environmental reduction represent different forms of evidence and cannot be combined into an overall technology ranking.

Table 2. Selected quantitative findings and their limits of interpretation.

Study and setting	Reported result	Interpretation boundary
UV-C treatment of cut roses Vega et al. (2020)	Conidial germination: 89.2% in unirradiated controls and 2.8% after the reported 1,080 J m^{-2} treatment.	Controlled postharvest assay; germination is not equivalent to shipping or vase-life performance.
Five greenhouse typologies Villagrán et al. (2022)	Spatial daytime temperature differences ranged from 2.7 to 7.2 °C among the evaluated structures; 40 sensors were used per structure.	Within-structure spatial differences; not a treatment effect or a measured flower-quality loss.
CFD validation Villagrán et al. (2021)	Temperature RMSE: 0.77 °C at 11:00 and 1.51 °C at 14:00 for the reported validation conditions.	Validation of physical predictions in one structure; not independent validation of crop yield.
Carnation thermal development Buitrago-Rueda et al. (2025)	Vegetative/reproductive base temperatures: 0.66/0.84 °C for Mizuky and 1.81/2.64 °C for Zafiro.	Parameters depend on cultivar and development stage; thermal-time totals require matching intervals.
Rose phenological detection Franco Montoya et al. (2025b)	Testing F1: 0.84 for the C_stage model and 0.72 for the multipurpose model; 2,000 images and 4,653 annotated objects.	Class-specific and multipurpose scores differ; new-farm performance was not established.
Carnation machinery Cuenca Orozco et al. (2024)	Company production summaries reported damaged stems decreasing from 6% to 2% after the modification.	An observed decrease of 4 percentage points in one case; no randomized multisite comparison.
Hydrangea cleaner production González et al. (2024)	Combined composting and reduced chemical-pesticide scenario: 16.59% lower modeled environmental load than the baseline.	Life-cycle scenario result; not a measured annual reduction across commercial farms.
Floriculture wastewater Benjumea-Hoyos et al. (2024)	Maximum observed removal: 80.9% for COD and 88.5% for color across experimental treatments.	The maxima occurred in different treatment results; neither value is a system-wide environmental benefit.

RMSE, root mean square error; F1, harmonic mean of precision and recall; COD, chemical oxygen demand. Values are not pooled because response variables, units, comparators and operating conditions differ.

Environmental performance and occupational outcomes

Environmental life-cycle assessment and life-cycle costing compared three production scales using a functional unit of 1 kg of stems, approximately 12 stems, over a 36-week production cycle, with the reported packaging and export-transport boundary (Arenas et al., 2024b). A separate cleaner-production assessment used the same mass-based unit for a 0.45-ha farm and modeled changes in residue and pesticide management (González et al., 2024). These shared definitions facilitate comparison, but overlapping sites or inventories may make the publications related evidence rather than independent replications. Their modeled environmental benefits remain conditional on inventory data, impact characterization and the proposed management scenario.

Social life-cycle assessment adds stakeholder and working-condition indicators that cannot be summed directly with environmental characterization factors (Arenas et al., 2024a). Likewise, electro-Fenton wastewater treatment evaluates removal within a defined process, while territorial analysis examines land use and social representations of birdlife (Benjumea-Hoyos et al., 2024; Sánchez-Ordoñez and Pyszczek, 2022). The wastewater results demonstrate treatment potential but require additional energy, chemical, residual-sludge and cost accounting before comparison with alternative systems. The territorial study provides context for habitat management without identifying a causal biodiversity loss attributable to floriculture.

Macroergonomic appraisal identified organizational limitations, qualitative research described the work–health experiences of women employed in floriculture, and task-allocation modeling considered repetitive work in job rotation (Pérez et al., 2021; Hernández-Bello et al., 2022; Saavedra-Robinson, 2023). A workday study measured increased leg volume after prolonged standing (Rodríguez et al., 2021b). The 2025 musculoskeletal-pain record similarly reported changes over a workday but contributes descriptive information because detailed report-level appraisal was not possible (Rodríguez et al., 2025). These studies support prospective evaluations of ergonomic interventions; they do not establish the size of a long-term reduction in injury following automation.

Export-competitiveness analyses describe market position, whereas a sectoral econometric study associated diagnosed cancer with reduced recorded productivity (Avendaño Ruiz et al., 2023; Gomez-Ramirez and Lis-Gutierrez, 2026). The latter association should not be interpreted as an independently estimated causal effect of pesticide exposure on cancer incidence. For technology assessment, the relevant contribution is recognition that labor, health and production costs can interact. Establishing causation or preventable burden would require different exposure and follow-up design.

Integration priorities and evidence limitations

The evidence supports complementary functions of characterization, monitoring, prediction and intervention, rather than a single ranking of technological maturity. Figure 2 organizes these functions and the validation needed to connect them. Improved environmental measurement becomes operationally useful when it changes a decision and produces a reproducible crop, resource or worker outcome. Consequently, integrating sensors, models and control devices should be assessed through a defined decision pathway, not through the number of technologies installed.

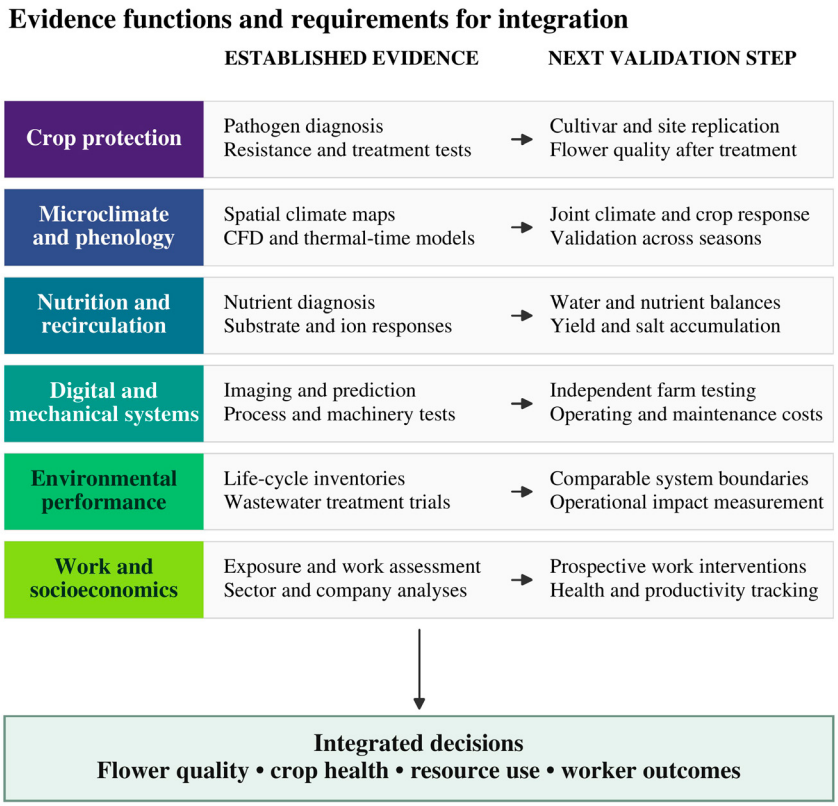


Fig. 2. Conceptual synthesis of evidence functions and validation priorities across the six review domains.

Three priorities follow from the comparison. First, replicated greenhouse trials should connect spatial microclimate, plant physiology, phytosanitary pressure and marketable stem quality. Second, predictive tools should undergo external validation across seasons, cultivars and farms before evaluation of their effects on operational decisions. Third, technology trials should measure resource use, salinity or waste accumulation, operating costs and worker outcomes within explicit boundaries. These priorities require standardized response definitions and accessible study metadata, while allowing crop-specific experimental designs.

The principal review limitations are its single-database, export-bounded sampling frame and the incomplete original search log. They prevent a claim of exhaustive coverage or complete search reproducibility. Three descriptively retained records also have less methodological documentation than the remaining reports. The critical appraisal is narrative and does not provide a formal risk-of-bias score, independent duplicate-review agreement or a pooled certainty assessment. These restrictions should be considered when interpreting the map as a research inventory.

The underlying studies impose additional limits. Several interventions concern a small set of cultivars or individual production sites, model evaluations differ in validation design, and environmental analyses depend on their functional units and scenarios. Related publications may share research settings or biological material. These features justify publication-level mapping and conditional interpretation of outcomes; they do not justify pooling percentages or treating every reported result as an independent estimate of commercial effectiveness.

Conclusions

Research on Colombian floriculture during 2020-2026 covers crop protection, greenhouse climate, phenology, nutrition, digital and mechanical processes, environmental performance and work-related outcomes. Its main contribution is a set of technically relevant, context-dependent findings whose value can be assessed through explicit experimental and analytical boundaries.

Reported climate gradients, thermal requirements, treatment responses, prediction metrics and environmental scenarios answer different questions. Their transfer to commercial decisions depends on cultivar and site coverage, comparators, independent validation, and measurements of flower quality or operational performance. Evidence of laboratory efficacy or model fit alone does not establish effectiveness at production scale.

The next research step is to test integrated decisions through replicated trials that connect environmental exposure, plant response, crop protection, resource flows and worker outcomes. Such trials would provide a stronger basis for selecting technologies that improve flower production while accounting for their environmental and social consequences.

Acknowledgments

There are no acknowledgments to be made.

Author Contribution

EV: Conceptualization, Resources, Writing – Review & Editing. **OMM:** Writing – Original Draft, Writing – Review & Editing. **RG:** Data Curation, Formal Analysis, Funding Acquisition, Investigation, Methodology, Writing – Review & Editing.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability Statement

Supplementary Table S1 (https://doi.org/10.6084/m9.figshare.34969819) provides the retained-publication register, bibliographic identifiers, thematic assignment and study-level interpretation boundaries. Supplementary Table S2 (https://doi.org/10.6084/m9.figshare.34969819) provides the 89-record selection log. The accompanying files also contain the values and source identifiers used in the figures and quantitative synthesis.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors declare that the use of AI and AI-assisted technologies was not applied in the writing process.

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