engineering proceedings

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Proceeding Paper

An Integrated Sustainable Floriculture Model Combining Soilless Propagation Systems, Auxin Optimisation and Industry 4.0 Automation †

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† Presented at the 2nd International Conference on Engineering, Technology, and Applied Science Innovations (ICETASI 2026), Zakynthos, Greece, 24–26 September 2026.

Abstract

Floriculture needs propagation protocols that combine biological efficiency with digital control. This synthesis integrates two factorial studies on *Salvia rosmarinus* and *Lavandula angustifolia* with a qualitative Industry 4.0 greenhouse pilot. In *Salvia rosmarinus*, the propagation system was the strongest source of variation in shoot height and root length ($F = 511.92$ and 226.62, respectively; $p < 0.001$); detailed Tukey comparisons placed the highest observed shoot- and root-length means in float treatments and the highest branching mean in mist, with several leading treatments statistically comparable. In *Lavandula angustifolia*, general linear model estimated marginal means indicated approximately 20–30% greater root length and greater branching under aeroponics than under mist or float; no post hoc multiple comparisons were available. Auxin-formulation responses were secondary and species-dependent. The PlantBot architecture links Internet of Things sensing, artificial intelligence, robotics, and radio-frequency identification, but has not yet been quantitatively validated for resource efficiency. The evidence therefore supports a hierarchical model in which system selection establishes the rooting environment, auxin provides conditional enhancement, and automation supports control and traceability. Future validation should include a true no-IBA control and automated-versus-conventional comparisons of biological performance, water, energy, labour, reliability, and cost.

Keywords: aeroponics; soilless propagation; auxins (IBA); Industry 4.0; sustainable floriculture

1. Introduction

Floriculture and aromatic medicinal plant production face increasing pressure to reduce water, energy, labour, and chemical inputs while maintaining uniform propagating material. The global cut-flower market was valued at approximately USD 39.08 billion in 2024 and is projected to reach USD 51.83 billion by 2030 [1]. This expansion, together with climate instability and rising production costs, strengthens the case for controlled, resource-conscious propagation technologies. Soilless systems can improve control of root-zone water, oxygen, and nutrients, while circular-production approaches can reduce substrate use and waste [2–5].

Aeroponics supplies nutrient solution as fine droplets to suspended roots, mist systems maintain high humidity around unrooted cuttings, and floating hydroponics provides

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Academic Editor: Konstantinos Poirazidis

Published: 10 November 2026

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continuous contact with an aerated solution [4–7]. Indole-3-butyric acid (IBA) is commonly applied as powder or gel, but formulation performance depends on species and rooting environment [8–10]. In parallel, Industry 4.0 tools—Internet of Things (IoT) sensing, artificial intelligence (AI), robotics, radio-frequency identification (RFID), and digital twins—offer monitoring, control, traceability, and predictive-maintenance functions [11–18]. These technologies, however, do not replace the need to select an appropriate biological propagation system.

This paper synthesises three complementary studies: factorial experiments on *Salvia rosmarinus* [6] and *Lavandula angustifolia* [7], and the PlantBot robotic-greenhouse pilot [18]. The objective is to develop and critically evaluate an integrated framework for the sustainable propagation of aromatic and medicinal Lamiaceae by: (1) comparing responses associated with aeroponics, mist, and floating hydroponics; (2) assessing species-specific responses to powder and gel IBA formulations; (3) identifying system–treatment combinations associated with shoot elongation, root elongation, and root branching; and (4) positioning the biological evidence within a testable Industry 4.0 framework for monitoring, traceability, and future commercial validation (Figure 1). The novelty lies in linking species-specific experimental evidence to a hierarchical automation framework, clearly separating measured outcomes from conceptual claims, and avoiding the assumption that one propagation system is universally superior.

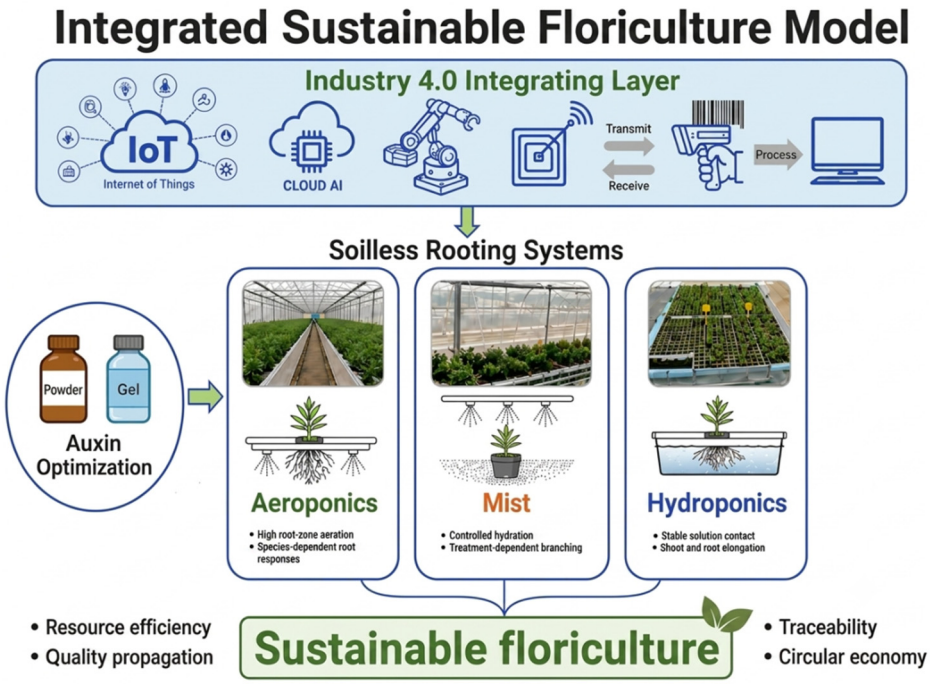


Figure 1. Conceptual structure of the integrated sustainable floriculture model, combining species- and treatment-dependent soilless propagation responses, targeted auxin use, and an Industry 4.0 layer for sensing, control, automation, and traceability.

2. Evidence Base and Quantitative Synthesis

The two propagation studies used completely randomised 3 × 2 × 7 factorial arrangements: three systems, two IBA formulations, and seven growth-retardant treatments, with 30 cuttings per treatment [6,7]. The control denoted the absence of growth retardant; neither experiment included a true no-IBA treatment. In *Salvia rosmarinus*, three-way analysis of variance (ANOVA) and Tukey's HSD were used. In *Lavandula angustifolia*, a general linear model (GLM) generated estimated marginal means, standard errors, and confidence intervals; replicate-level data were unavailable for post hoc multiple comparisons. The

https://doi.org/10.3390/engproc2026167015

PlantBot study contributed architecture and process flow only and reported no measured resource or economic performance [18].

Accordingly, rosemary findings can be interpreted using inferential group comparisons, whereas lavender findings are model-based quantitative trends. Table 1 summarises the evidence without treating the three source studies as methodologically equivalent.

Table 1. Quantitative evidence and limitations of the three source studies.

Evidence Source	Analytical Basis	Quantitative Result	Interpretation
Salvia rosmarinus [6]	Three-way ANOVA and Tukey HSD	System effects: shoot height $F = 511.92$; root length $F = 226.62$; lateral roots $F = 113.61$; all $p < 0.001$. Three-way interactions were also significant ($p < 0.001$).	Float had the highest observed shoot- and root-length means; mist had the highest observed branching mean, but leading treatments shared Tukey groups.
Lavandula angustifolia [7]	GLM estimated marginal means ± SE and 95% CI; no post hoc test	Aeroponics was associated with approximately 20–30% greater estimated root length and greater estimated branching than mist or float; gel showed stronger estimated root responses than powder.	Quantitative model-based trends, not confirmed pairwise differences.
PlantBot [18]	Qualitative pilot architecture	No measured rooting, water, energy, labour, reliability, or cost outcomes.	Conceptual integration layer requiring controlled validation.

3. Integrated Findings

3.1. Propagation Systems

Aeroponics provides intermittent nutrient mist and high root-zone aeration, conditions that may favour root elongation and branching [4,5]. In *Lavandula angustifolia*, aeroponics was associated with the strongest estimated root responses [7]. In *Salvia rosmarinus*, however, aeroponics produced shorter shoots and did not yield the highest overall branching mean [6]. This species contrast shows that oxygenation alone does not determine performance; treatment interactions and target traits remain decisive. Physiological explanations involving respiration, auxin transport, or root–shoot allocation are plausible but were not directly measured [9,10].

Mist reduces desiccation before functional roots form and, in rosemary, supported a top branching treatment when combined with powder IBA and low daminozide [6]. Floating hydroponics provides stable solution contact and produced the highest observed rosemary shoot- and root-length means, although leading mist treatments were statistically comparable. Float also favoured estimated shoot elongation in lavender [7]. Thus, aeroponics is most relevant when root architecture is the priority, mist when controlled hydration and branching are desired, and float when operational stability and elongation are important; none can be claimed universally superior or economically preferable without direct cost and resource measurements.

3.2. Auxin Formulation

Auxin responses were secondary to broader system-associated patterns and differed by species. Powder IBA generally supported stronger selected responses in *Salvia rosmarinus*, whereas gel was associated with greater estimated root responses in *Lavandula angustifolia* [6,7]. The studies did not measure auxin uptake, formulation retention, stem anatomy, or surface wettability, so mechanistic explanations remain hypotheses. Auxin is most useful for difficult-to-root genotypes, suboptimal seasons, or production targets requiring rapid and uniform rooting. Optimisation should use species- and system-specific dose–response

trials that include rooting percentage, time to root emergence, biomass, mortality, and post-transplant establishment [8–10]. A decisive experiment must include no IBA, powder IBA, and gel IBA at equivalent active-ingredient concentrations; growth retardants should initially be excluded or held constant.

3.3. Industry 4.0 Integration and Validation

PlantBot organises greenhouse production into sensing, communication, cloud decision support, and actuation layers [18]. IoT–AI control has the greatest potential direct influence on propagation because it can regulate spray timing, relative humidity, vapour-pressure deficit, nutrient-solution temperature, pH, electrical conductivity, and dissolved oxygen. Robotics and automated guided vehicles mainly affect handling and labour; RFID supports traceability; digital twins support simulation and predictive maintenance [11–18]. These functions are enabling technologies, not evidence that the integrated system already improves resource efficiency.

Validation should compare fixed conventional control with sensor-based automated control within each propagation system while holding plant material, auxin, nutrition, and greenhouse conditions constant. Biological indicators should include rooting percentage, time to root emergence, root and shoot traits, mortality, uniformity, and post-transplant survival. Operational indicators should include water and nutrient discharge per marketable cutting, electricity, labour, downtime, maintenance, and cycle duration. A techno-economic analysis should calculate annualised equipment cost, cost per marketable cutting, and break-even conditions [11–17,19]. AI models would require time-series sensor data and treatment metadata; the existing endpoint datasets are suitable for hypothesis development but insufficient for robust operational training.

4. Integrated Model and Future Research

The model is hierarchical. Propagation-system selection establishes the physical rooting environment; auxin provides conditional, species-specific enhancement; Industry 4.0 adds monitoring, adaptive control, automation, and traceability; and circular-economy principles define resource-recovery and waste-reduction objectives [2,3,20]. Removing the propagation system would have the greatest immediate biological consequence, whereas removing automation would leave propagation operational but less controllable and traceable. Extension to another medicinal species requires renewed screening of stem maturity, endogenous rooting capacity, disease susceptibility, environmental set points, nutrient solution, sensor calibration, sanitation, and failure tolerance before automated or economic optimisation. The framework therefore converts the three source studies into a testable programme rather than a claim of completed commercial validation.

5. Conclusions

The synthesis shows that propagation outcomes are species-, system-, treatment-, and trait-dependent. Rosemary inferential analyses identified strong system and interaction effects; float produced the highest observed elongation means and mist the highest observed branching mean, with several top treatments statistically comparable. The lavender model estimates associated aeroponics with 20–30% greater root length and greater branching, but formal post hoc comparisons were unavailable. Powder and gel IBA responses likewise differed between species, and the absence of a true no-IBA control limits causal separation of physical and hormonal effects.

Industry 4.0 should therefore be regarded as a conceptual integration layer rather than a validated efficiency outcome. Commercial adoption requires controlled automated-versus-conventional trials and biological, resource, reliability, and cost indicators. The practical

recommendation is not to select one universal technology, but to match the propagation system and auxin treatment to the species and target trait, then add automation only where measured benefits justify its complexity and cost.

Author Contributions: Conceptualization, G.L. and V.T.; methodology, G.L. and A.L.-T.; investigation, G.L.; writing—original draft preparation, V.T.; writing—review and editing, G.L., A.L.-T. and V.T.; supervision, A.L.-T. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data were obtained from the published studies and are available from the authors with permission. Quantitative findings were drawn from the published propagation studies [6,7], and the automation architecture from the qualitative pilot [18].

Acknowledgments: During the preparation of this manuscript, the authors used Claude (Anthropic, Claude Opus 4.1) for the purposes of language editing and improving the readability of the text. The authors have reviewed and edited the output and take full responsibility for the content of this publication.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

ANOVA	Analysis of Variance
GLM	General Linear Model
SE	Standard Error
CI	Confidence Interval

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