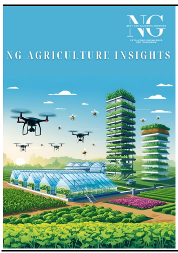

NG Agriculture Insights

A Popular Magazine (ISSN: 3107-5703)

Volume 2, Issue 5, September-October, 2026, 1-7

Smart and Sustainable Vanilla Production through Soilless Organic Cultivation and IoT-Based Precision Management

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A B S T R A C T

The vanilla (*Vanilla planifolia* Jacks. ex Andrews) is a valuable orchid whose growth, yield, and quality are dependent on genotype, micro-climate, rhizosphere, nutrients, and biotic stresses. The conventional cultivation methods usually operate under variable environmental conditions, hence there is the need for smart climate and resource efficient farming methods. This paper proposes an integrated approach to the precision farming of vanilla, which applies the equation P = G + E + (G×E), in which the performance of the plants is viewed as a function of genotype, environment and their interaction. The proposed approach combines the use of greenhouse farming, soilless substrate systems from locally available materials, IoT-based micro-climate monitoring, precision irrigation via foggers, organic nutrients, and good agricultural practices. There is particular attention paid to the interaction between the availability of macronutrients and micronutrients and environmental factors influencing the growth, yield, and quality of vanilla. Additionally, the biotic stress caused by *Fusarium oxysporum* will be taken into account. Another important dimension that needs to be considered is the connection between abiotic stress and the formation of secondary metabolites, especially those associated with the formation of vanillin compounds. By combining the environmental monitoring, precision irrigation and nutrition practices, disease management and production of good quality of produce, the suggested system will offer a means of converting traditional vanilla cultivation under protective conditions into climate-smart precision production. This is especially applicable to trellis based cultivation systems of vanilla where local materials and irrigation techniques can be used in conjunction with each other.

Keywords: *Vanilla planifolia*, Climate-Smart Agriculture, P = G + E + G×E, Soilless Cultivation, Precision Irrigation

Submitted: 18-08-2026 Accepted: 21-08-2026 Online: 01-09-2026

1. INTRODUCTION

Vanilla (*Vanilla planifolia* Jacks. ex Andrews) is a high-value orchid crop whose productivity and quality are strongly influenced by climate, root-zone conditions, nutrition, plant health and management. Conventional soil-based production exposes the crop to seasonal variation in temperature, rainfall, humidity and soil moisture. Additionally, the vanilla plants are prone to root and stem rot (RSR) caused by *Fusarium oxysporum* f. sp. radicis-vanillae (Forv) and stem blight caused by *Phytopthora* sp. cause severe crop loss under open environment. The diseases caused by soil-born

https://doi.org/10.5281/zenodo.22070348

fungus and difficult to manage in open environment causes significant yield loss up to 80% in solanaceous crops and up to 60-90% in cucurbits (Dash *et al.,* 2021). A climate-smart protected system therefore needs to do more than provide shade: it should create a measurable and manageable production environment.

Vanilla planifolia is monopodial orchid prefers tropical warm and humid environment though the performance is greatly varied due to genotype × environment interactions which highlighted by many researchers (Asfaw *et al*., 2009; Elias *et al*., 2026; Pramanik *et al*., 2024). A useful framework for understanding this response is P = G + E + (G×E), where P represents observed phenotypic performance, G the genotypic component, E the environmental component and G×E the differential response of genotype to environment. The same planting material may express different growth, yield or quality under different environmental conditions. For vanilla, this relationship is particularly relevant because temperature, humidity, light, water availability, nutrition and disease pressure influence vegetative growth, flowering, pod development and biochemical quality. Vanilla is a sessile plant and sensitive to environment fluctuations, which affects production of vanillin as important secondary metabolites. The vanillin biosynthesis is control by expression of VpPAL1 gene (Fock-Bastide *et al*., 2014). However, the gene expression is directly by occurrence of abiotic stresses such as high temperature, low relative humidity and elevated CO_2 levels (Pradhan *et al*., 2024). The concept can be applied directly to vanilla production. Genotype is represented by the planting material, while environment includes temperature, relative humidity, light, substrate moisture and root-zone conditions. Precision irrigation, fogging, nutrition, support, sanitation and disease management then provide tools for managing the production environment. The objective is not to eliminate environmental variation but to reduce avoidable stress and provide conditions in which the genetic potential of healthy vanilla plants can be expressed consistently. The present perspective is based on ongoing work with a vanilla dome and low-cost protected unit in Centurion University of Technology and Management, Gajapati, Odisha incorporating soilless media, IoT-enabled monitoring, fogger-based precision irrigation, organic nutrient management and disease-management practices. The framework also integrates the effects of macronutrients and micronutrients on growth, total yield and quality and connects climate and stress with secondary metabolism, including vanillin-associated qualities.

2. VANILLA CROP PHYSIOLOGY RELEVANT TO PRECISION CULTIVATION

2.1 Hemi-epiphytic growth habit and root physiology

Vanilla is a climbing, hemi-epiphytic orchid with aerial and substrate-associated roots. The root-zone therefore needs both moisture and aeration. A production system that maintains high atmospheric humidity while creating prolonged root-zone saturation may increase physiological and disease problems. Canopy humidity and substrate moisture should consequently be treated as connected but distinct variables.

2.2 Microclimatic sensitivity

Temperature, relative humidity and light influence plant physiological activity. Protected cultivation can buffer abrupt changes, but excessive humidity combined with poor ventilation and persistent wetness can favour disease. Conversely, inadequate moisture may restrict establishment and growth. The purpose of a vanilla dome should therefore be controlled microclimate rather than simply high humidity.

2.3 Phenology

The production system must accommodate vegetative establishment, vine growth, flowering, hand pollination, pod set and pod development. Environmental requirements and water demand may differ among stages. Stage-specific monitoring and irrigation are therefore preferable to a single fixed schedule.

2.4 Physiological basis for soilless/substrate suitability

Vanilla is sensitive to waterlogging condition. Therefore, heavy textured soil is not suitable for growing vanilla. Additionally, it carries soil-borne pathogens causes stem and root rot. A suitable substrate should provide optimum water retention, drainage, porosity and root support. These characteristics are central to maintaining the balance between water availability and aeration.

3. SOILLESS ORGANIC PRODUCTION SYSTEMS

3.1 Soilless media

The soilless media comprises of cocopeat, wood charcoal, coconut chips, vermicompost and burnt rice-husk ash are rich in organic carbon and have good water and nutrients retention facilitates proper aeration, better anchoring and well drainage. Cocopeat provides a fibrous moisture-retentive matrix; charcoal can contribute structural porosity; vermicompost supplies organic matter and nutrients; and ash may contribute mineral elements. The media are mixed in different proportion such as two parts cocopeat, one part wood charcoal, one part coconut chips, one part rice burnt ashes and one part vermicompost for vanilla growing. The nutrient contents and physiochemical properties may be different depending on preparation of the sole media and mixture. A recent V. planifolia water-stress experiment used a growing medium containing soil + cocopeat + rice-husk charcoal + manure (2:1:1:1) and evaluated moisture at 25%, 50%, 100%, 150% and 200% field capacity. Important parameters include pH, EC, water-holding capacity, porosity, bulk density, drainage and nutrient status. These measurements are especially important in a small root-zone because excessive EC or poor drainage can restrict plant performance even when the aerial environment is favorable. Vanilla prefers pH of 5.5–6.5 and EC of 0.6–1.2 mS/cm apart from which the crop suffers salinity and alkalinity stress affecting growth and development. In soilless vanilla cultivation, maintaining a relatively low root-zone EC is important because excessive nutrient concentration may impose osmotic stress and alter root development and plant metabolism. Recent evidence indicates that *V. planifolia* responds favorably to comparatively low nutrient-solution EC, while higher EC can affect root development and secondary-metabolite profiles (Vahl *et al*., 2026).

3.3 Container/bag culture versus raised-bed soilless troughs

Containers, bags and raised tray offer different possibilities for root-zone control, labor and drainage. The low-cost option should be selected according to local material availability, ease of sanitation, plant support and irrigation arrangement. The growing bed can be prepared with grow bags, anti-weed mulch or any UV-stabilized polyethene. A recent controlled study specifically used *Vanilla planifolia* in individual 11-cm polyethylene containers filled with perlite for soilless culture. The experiment evaluated nutrient-solution pH and EC and demonstrated that vanilla can be experimentally grown in a controlled soilless container system (Vahl *et al*., 2026). For raised-bed production, there is evidence from commercial vanilla production rather than a controlled scientific comparison. A documented Hawaiian vanilla farm used a raised-bed system with plants suspended above the ground, specifically to reduce root-rot problems. The UF/IFAS vanilla production guide also describes planting *V. planifolia* cuttings into a growth substrate and discusses hardening tissue-culture plants in soilless mix (Chambers *et al*., 2019).

3.4 Trellis and plant support system

The support system is an essential part of vanilla production because it influences vine training, canopy distribution, pollination and harvest. The vanilla dome situated at Centurion University of Technology and Management; Odisha is a modular rotary trellis system consists of a number of self-contained trellises which are connected to the central hub offer uniform distribution of diffused sunlight. The 3D aspect ensures optimal habitation biomass within a special area to effect high growth and productivity for plants. The central hub allows manual or motorized rotation which in turn will rotate each of the connected trellis arms. The rotation displaces each connected trellis to effect solar orientation. The invention comprises three main structural modules **a)** vertical cylindrical trellis **b)** rolling trellis base **c)** central rotary hub. Each module is designed to be flexible, allowing changes to specifications to optimize the requirements of the desired plantae.

Figure 1. Trellis based soilless vanilla cultivation

3.5 Vanilla dome and low cost polyhouse

The dome is geodesic structure, measured dimensions of 2000 feet^2 diameter at base made up of aluminum frame, covering with UV-stabilized polyethylene and shade net to avoid scorching sunlight penetration and heat build-up inside provided with four vents for ventilation. The dome consists of rotatory trellis system for providing support system to vanilla vines. Sensor or acutors are installed inside the dome for real time recording of temperature, relative humidity and CO_2. The dome has been constructed with collaboration of Vanilla Plantation Group, Sydney with fixed cost of seventeen lakhs part from recurring cost. A low-cost vanilla unit has been constructed with natural-ventilated polyhouse consisting of raised beds with soilless media, foggers and fan for ventilation. The low-cost model has been established with total cost of three lakhs for research and demonstration purpose particularly to evaluate the overall performance of vanilla as compared to dome and natural environment.

Figure 2. Overview of Geodesic vanilla dome

Figure 3. Low cost vanilla unit

4. IoT-BASED MICROCLIMATE MANAGEMENT

IoT provides the information layer of precision vanilla production. Depending on the actual system, temperature, relative humidity, substrate moisture and light can be monitored continuously. The IoT system comprised of sensor, data acquisition, Decision/threshold, Fogger or irrigation/ventilation, environmental response and Feedback. This converts a passive protected structure into a responsive production unit. The dome compromised of a well efficient automation system enabled with sensor to detect micro environments including temperature, relative humidity, carbon dioxide and media moisture. The automation facilitates uniform sunlight distribution on the plant trellis by slow sequential rotation of central rotary hub as per sun orientation. Vanilla requires optimum temperature, relative humidity, CO_2 and media moisture i.e., 25-35^{0}C, 75-80%, 350-400 ppm and 60–75% of field capacity respectively for growth and development. The most important principle is that sensors must support decisions rather than simply generate data. For example, substrate moisture guide irrigation, while temperature and RH can guide fogging.

5. PRECISION IRRIGATION AND FERTIGATION

Fogging may assist in achieving microclimate regulation and water supply, but increased RH does not necessarily mean adequate root zone water content. Excessive fogging could create permanent wetness and disease occurrence. Hence, monitoring of irrigation/fogging rate, duration, amount of water available when used, moisture of substratum, temperature, and RH is done using Internet of Things.

5.1 Macronutrient and micronutrient management

Nutrition plays a very vital role in determining the performance of the plant. The elements like nitrogen, phosphorus, and potassium are needed for growth and reproduction, and other secondary and microelements are needed in structural, enzyme and physiologic functions. In another 2026 experiment done without soil using *V. planifolia* in perlite pots, 200 mL of nutrition were added to each pot bi-weekly in order to prevent waterlogging of vanilla plants (Vahl *et al.*, 2026). Vanilla is micronutrient loving spice crop like onion, which prefer major micronutrients such as boron, iron, zinc, and manganese for growth, yield and quality particularly increasing pungency level (Pramanik and Tripathy, 2017; Pramanik *et al*., 2018). Among major macronutrients, phosphorus is an important macronutrient for *V. planifolia*, with experimental studies indicating its association with vegetative growth, nutrient status and reproductive performance. In greenhouse-grown vanilla, adequate P supply was associated with improved growth, while low foliar P was identified as a potential nutritional limitation. Fertilization containing P has also been reported to improve flowering and fruiting performance (Ruhnayat, 2007; Diez *et al*., 2016). The application of phosphorus equally influenced the growth and yield components as well as yield of cowpea (Sudharani *et al*., 2018).

6. GOOD AGRICULTURAL PRACTICES (GAP) INTEGRATION

6.1 Panting material

Vanilla has different species such as *Vanilla planifolia, Vanilla × tahitensis* and *Vanilla pompon* (Bory *et al*., 2008) among which the Vanilla planifolia is called as Flat-leaved vanilla or Bourbon vanilla is most popular and widely grown species, providing a rich, creamy, and traditional sweet flavor profile. When grown in the Indian Ocean region. A well rooted, disease free vanilla vines with approximately 60–120 cm length, with 15–20 internodes and 13–15 leaves, as suitable planting material (Reddy and Shukla, 2007).

Table 1. Foliar application of organic substances for nutrients and pest management

Source	Doses 10L^{-1}	References
Vermiwash	10% (1litre)	
Amritpani	3% (300ml)	Ram *et al.* (2018)
Bio-decomposer	3% (300ml)	Singh *et al.* (2022)
Ganajibamruta	3% (300ml)	Ram *et al.* (2018)
CUTM Microbial Consortium	0.3% (30ml)	
Dashagavya	3% (300ml)	Vaish *et al.* (2020)
Panchgavya	3% (300ml)	Manimaran and Prakash, (2018); Ram *et al.* (2018)

6.2 After care

Vanilla post-planting needs to be subjected to constant vine training, moisture control, nutritional balance, shading, mulching, and disease management. The vines need to be trained over support structures and sometimes looped down to achieve optimal canopy formation and rooting at optimal nodes. The root zone should be maintained moist but well drained, avoiding prolonged waterlogging, while organic mulching helps conserve moisture and moderate root-zone temperature. Balanced macro- and micronutrient application should be guided by plant growth and soil/substrate conditions. Adequate filtered light, humidity and ventilation should be maintained, and weeds should be controlled without disturbing the shallow root system. During flowering, timely hand pollination is essential for successful pod set. Regular inspection for *Fusarium oxysporum* and other diseases, together with healthy planting material, sanitation and proper drainage, is important for disease prevention. In precision production systems, monitoring of temperature, relative humidity, substrate moisture, pH and EC can support timely irrigation, fogging and nutrient-management decisions.

6.3. Pollination management

Pollination is one of the most critical management operations in commercial vanilla production because the floral structure of *Vanilla planifolia* restricts natural self-pollination. The rostellum, a membranous structure between the anther and stigma, prevents direct contact between pollen and the receptive stigma (Van Dyk *et al*., 2024), and commercial production therefore depends almost entirely on hand pollination. Each flower remains open for only a single day, so pollination must be completed on the same day it opens, preferably in the morning (Van Dyk *et al*., 2024). Research at Kerala Agricultural University's Regional Agricultural Research Station, Ambalavayal, found 97.5–100% success when hand pollination was carried out between 6 am and 6 pm (KAU–RARS Ambalavayal), while floral-biology observed that 6:00 am–1:00 pm as the effective window for good fruit set, even though the stigma itself stays receptive for up to 24 hours (Van Dyk *et al*., 2024). Hand pollination is conducted using a toothpick, piece of bamboo or another such slim object that lifts the rostellum and touches the pollinia (the anther carrying pollen) to the stigma (Van Dyk *et al*., 2024). Successful pollination is followed by pod development, whereas unsuccessful flowers typically drop within one to three days. For commercial quality, fruit load per inflorescence is also controlled, with 5–6 flowers per inflorescence and around 10–12 inflorescences per vine commonly recommended to avoid overburdening the vine.

6.4 Pest and disease management under protected soilless systems

In recent past the crop is suffered with multiple disease and insect attack. For instance, in 2019 there is outbreak of root and stem rot (RSR) caused by *Fusarium oxysporum* f. sp. radicis-vanillae (Forv) and stem blight caused by *Phytopthora* sp. cause severe crop loss in Karnataka which is leading states in vanilla cultivation. Farmer Keremane Bharath said, “Last year, I could procure eight quintals of vanilla in and around Sringeri. This year, I may get half of it. The crop is more cultivated in Kerekatte and Nemmar of Karnataka states. The vanilla creepers fail to thrive in the place where the plant was infected with disease. *Fusarium oxysporum* is a major disease concern in vanilla. Infection can damage roots and stems, reduce water and nutrient uptake, cause vine decline and reduce yield. Disease therefore becomes part of the environmental component affecting phenotype. A genotype that appears vigorous under low disease pressure may perform very differently under a disease-prone environment. Under organic protocols, pest and disease management in protected soilless systems begins with prevention- sanitation, insect-screened vents, adequate spacing for airflow, and sterilized growing media address most risk before any input is applied (Schnitzler, 2004)- and is then reinforced with biocontrol agents such as *Trichoderma viride*/*T. harzianum*, applied as a root dip or substrate drench to suppress soil-borne pathogens like *Fusarium* through mycoparasitism, alongside *Bacillus subtilis* and *Pseudomonas fluorescens* as microbial antagonists and *Purpureocillium lilacinum* for nematode control (Patil *et al.,* 2022). The neem-based preparations (in the form of oil, cake, and leaves) can act as an insect repellent and anti-fungal agent, in combination with copper-based organic fungicides and sticky and pheromone traps, and constitute a natural IPM strategy that suits the soilless vanilla polyhouse environment, where Trichoderma is inoculated along with stringent sanitation to counter the Fusarium wilt problem (Farmonaut, 2025).

6.5 Maturity and Harvesting

The beans take about 8-9 months to attain maturity after hand-pollination and when the pods start developing a slight yellow colour at the tips with the rest of the pod green before harvesting manually at the base without injuring any adjacent flower or immature pod. When harvested, the green beans lack any aromatic characteristics as the flavor molecules are present in the form of bound glucoside precursors which can only be activated through curing process (Cuan-Escobar *et al*., 2025). The curing process is therefore accomplished through four classic stages namely killing (blanching using hot water or any other heat process to arrest vegetative growth and activate enzymes), sweating (keeping in hot and humid air-tight environment for enzyme and oxidative formation of aroma), drying in the sun alternatively with sweating for several weeks in order to decrease the moisture content without growing any mold and conditioning (storage for several months to allow esterification and other maturing reactions) (Cuan-Escobar *et al*., 2025; Aayuluxe, 2026). Killing phase is especially important as the efficiency and time required for this phase are directly proportional to the final yield of vanillin. Use of water killing method at 65°C for one minute gives the highest yield in vanilla. The entire process of killing up to conditioning takes about 3 to 8 months depending on the technique and weather.

7. FUTURE PROSPECTS

Future work should extend the IoT-based monitoring layer toward AI-driven predictive control using sensor time-series (temperature, RH, CO_2, substrate moisture, EC) to forecast disease-conducive conditions and trigger pre-emptive fogging, ventilation or biocontrol application rather than reactive thresholds alone. Genotype screening and selection for *Fusarium*-tolerant vanilla accessions, combined with molecular markers linked to VpPAL1 expression, could allow genotype × environment optimization to move from a conceptual framework toward applied breeding and clonal selection for soilless systems. Scaling the substrate and trellis protocols validated in the dome and low-cost unit to smallholder-replicable, low-capital models with simplified sensor packages and locally sourced media is essential if the approach is to translate beyond a research demonstration into commercial adoption in Odisha and similar agro-climatic zones. Further controlled studies correlating root-zone EC, micronutrient status and abiotic stress with vanillin and precursor-compound accumulation would strengthen the link between precision management and cured-bean quality, which currently rests on indirect and largely secondary evidence.

8. CONCLUSION

In this paper, a climate-smart integrated approach towards precision vanilla farming using the model P = G + E + (G×E) has been presented where soilless organic substrate farming, Internet of Things (IoT) technology-driven microclimate monitoring, precision fogging/ irrigation, organic nutrition and disease management and finally a rotary trellis system have been combined. Instead of considering genotype, environment and their interaction as uncontrollable, the approach provides a way to overcome the problem of yield loss due to Fusarium and achieve stabilization of the root-zone and canopy microenvironment along with consistent pod yield and vanillin content of pods. This is supported by the successful development of the CUTM vanilla dome and the cost-effective version of this setup in Odisha.

ACKNOWLEDGEMENT

The authors sincerely acknowledge the Centurion University of Technology and Management, Odisha and Australian Vanilla Plantations, Sydney for the vanilla project established at Centurion University of Technology and Management, Paralakhemundi, Gajapati, Odisha from which original contents and images have been documented. The author also acknowledges Dr. Ashish Ranjan Dash and Mr. Mir Sadat Ali for providing necessary information for preparation of the article.

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