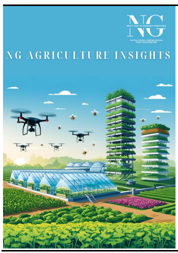

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From Vanilla to Vanillin: Sustainable Processing, Secondary Metabolites and Value-Added Products

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A B S T R A C T

The value of vanilla (*Vanilla planifolia* Jacks. ex Andrews) extends beyond pod production because its commercial importance is closely associated with the biochemical transformation of harvested pods during curing and the development of vanillin and other aroma compounds. Vanilla quality is therefore the outcome of interactions extending from genotype and growing environment to nutrition, plant health, pod development, curing and processing. This article presents a farm-to-vanillin framework based on linking biotic and abiotic factors with plant performance and subsequent biochemical quality. The framework incorporates the effects of macronutrient and micronutrient management on growth, total yield and quality and emphasizes the importance of balanced nutrition in determining the characteristics of pods entering the post-harvest chain. *Fusarium oxysporum* is considered as an important biological stress factor because disease can reduce plant vigour, nutrient and water acquisition and pod productivity, while potentially influencing physiological and biochemical responses. Particular emphasis is placed on secondary metabolism and the biosynthesis of vanillin in relation to abiotic stress, providing a conceptual bridge between climate-smart cultivation and final product quality. Traditional curing, enzymatic transformation, sustainable extraction, authentication and value-added products are incorporated into an integrated production-to-processing framework. The article provides opportunities for integrating horticulture, plant physiology, plant pathology, biotechnology, precision agriculture and food chemistry for sustainable vanilla value-chain development.

Keywords: *Vanilla planifolia*, Vanillin, Secondary Metabolites, *Fusarium oxysporum*, Value Addition

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1. INTRODUCTION

Vanilla (*Vanilla planifolia* Andrews) is one of the world's most valuable and widely used natural flavour crops, belonging to the family Orchidaceae. It is a perennial climbing orchid primarily cultivated in tropical and subtropical regions where warm temperatures, high humidity, adequate rainfall and partial shade favour vegetative growth and bean development. Global vanilla production remains concentrated in Madagascar (2,400–4,300 tonns year^{-1}), Indonesia and Uganda, while India cultivates roughly 24,000 ha across Kerala, Karnataka and Tamil Nadu, contributing only a minor share of world output (Mordor Intelligence, 2026; Francis, 2006). Natural vanillin supplies just 1,200–3,000 tonns of the approximately 59,000–60,000 tonns global vanillin

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market, the rest being synthetic, since 1 kg of natural vanillin requires apparently 500 kg of hand-pollinated pods (Mordor Intelligence, 2026; Grand View Research, 2026). Yield and quality are constrained by biotic stress, chiefly *Fusarium oxysporum* f. sp. *radicis-vanillae* root and stem rot impairing water and nutrient uptake and abiotic stress, where high temperature, low humidity, elevated CO_2 and water deficit modulate *VpPAL1* expression and vanillin biosynthesis (Fock-Bastide et al., 2014; Pradhan et al., 2024; Avianto, 2025). Root-zone nutrition, especially phosphorus, micronutrients (B, Fe, Zn, Mn) and low EC (0.6–1.2 mS/cm), further governs growth and secondary-metabolite accumulation (Osorio et al., 2014; Vahl et al., 2026).

Vanillin is the principal flavour compound responsible for the characteristic aroma of cured vanilla and represents an important phenolic secondary metabolite. It is chemically known as 4-hydroxy-3-methoxybenzaldehyde. Although vanillin occurs naturally in cured vanilla beans, its concentration and quality depend strongly on genotype, environmental conditions, maturity, harvesting stage and post-harvest processing. During curing, biochemical transformations convert precursor compounds, particularly glucovanillin, into free vanillin through enzymatic hydrolysis. Consequently, curing is a critical stage that determines the flavour, aroma, colour and commercial quality of vanilla. Besides vanillin, vanilla contains several secondary metabolites, including vanillic acid, *p*-hydroxybenzaldehyde, *p*-hydroxybenzoic acid, phenolic compounds, flavonoids and other volatile aromatic constituents, which contribute to its antioxidant, antimicrobial and functional properties.

The development of sustainable vanilla processing and value-added products provides an opportunity to increase the income and resource efficiency of the vanilla sector. Integrating vanilla cultivation, efficient curing, green extraction, secondary-metabolite recovery and product development can therefore establish a circular and sustainable value chain, transforming vanilla from a traditional flavour crop into a multifunctional source of natural flavour compounds, antioxidants and innovative value-added products. The article offers a comprehensive study on vanilla production under controlled environment to manage factors affecting the crop performance and efficient processing techniques resulting vanillin and other secondary metabolites.

2. PREHARVEST FACTORS INFLUENCING VANILLA GROWTH, YIELD AND QUALITY

2.1 Media mixture, cultural practices and input management

Preharvest performance in vanilla attributed to cultural practices, nutrition, growing media, irrigation and hand pollination rather than any single factor. Cultural operations such as vine training, periodic looping/lowering for canopy management, pollination, shade regulation, mulching and sanitation maintain the balance between adequate light interception and root-zone moisture that a hemi-epiphytic climber requires, with poor training or excess humidity favouring both physiological stress and disease incidence (Anandaraj *et al.*, 2005). Nutrient management is similarly decisive: phosphorus availability is closely linked to vegetative growth and reproductive performance in V. planifolia (Ruhnayat, 2007; Osorio *et al.*, 2014; Diez *et al.*, 2016), an effect consistent with earlier findings that phosphorus application significantly influences growth and yield components in cowpea (Sudharani *et al.*, 2018). Micronutrients viz., boron, iron, zinc and manganese are similarly critical in vanilla as in other micronutrient-responsive spice crops. Earlier work demonstrated that these elements govern growth, yield and quality (including pungency) in onion, underscoring their broader relevance to spice-crop nutrition (Pramanik and Tripathy *et al.*, 2017; Pramanik *et al.*, 2018). Soilless media composition (cocopeat, charcoal, rice-husk ash, vermicompost) governs aeration, drainage and root-zone EC/pH, with low EC (0.6–1.2 mS/cm) and pH 5.5–6.5 favouring healthy root development and secondary-metabolite profiles (Vahl *et al.*, 2026). Irrigation must likewise be precisely managed rather than frequent, since vanilla is waterlogging-sensitive; controlled trials restricting nutrient-solution delivery to fortnightly intervals, and water-stress experiments across a range of field-capacity levels, both confirm that moisture excess or deficit directly affects growth, CO_2 assimilation and cured-bean vanillin quality (Vahl *et al.*, 2026; Avianto, 2025).

2.2 Biotic and Abiotic Stresses

Fusarium oxysporum is the dominant biotic threat to vanilla, causing root and stem rot (Forv) that damages roots and vascular tissue, impairs water/nutrient uptake and drives vine decline- mirroring its broader destructiveness across crops, where Fusarium-associated soil-borne disease causes yield losses up to 80% in solanaceous crops and 60–90% in cucurbits (Dash *et al.*, 2021), making sanitation and disease-free planting material central to precision cultivation. Abiotically, vanillin biosynthesis is governed by VpPAL1 expression, which correlates with vanillin accumulation during pod development (Fock-Bastide *et al.*, 2014) and is itself modulated by high temperature, low humidity and elevated CO_2 (Pradhan et al., 2024); water stress further reduces CO_2 assimilation and photosynthetic capacity, affecting both growth and cured-bean vanillin quality (Avianto, 2025), while excessive root-zone EC imposes osmotic stress that alters root development and secondary-metabolite profiles, with V. planifolia performing best at EC 0.6–1.2 mS/cm and pH 5.5–6.5 (Vahl *et al.*, 2026).

3. POSTHARVEST FACTORS AFFECTING VANILLA AND VANILLIN PRODUCTION

3.1 Maturity indices

Vanilla pods must be harvested at a precisely defined maturity stage, since immature beans lack the full-bodied aroma and colour developed during curing and are more prone to fungal infection, while over-ripe pods split on the vine and lose aroma compounds before processing. The standard visual index is a slight yellowing at the apical tip while the rest of the pod remains green, corresponding to the point of maximum glucovanillin (the principal vanillin precursor) accumulation (Van Dyk *et al.*, 2014). Because this window is narrow and largely irreversible once missed, maturity assessment is arguably the single most consequential preharvest-to-postharvest decision point, directly setting the ceiling on achievable cured-bean quality regardless of how well curing is subsequently managed.

3.2 Harvesting procedure

Beans are hand-cut individually at the base to avoid damaging adjacent flowers, immature pods or the vine itself, and are typically sorted by maturity stage at harvest since mixed-maturity batches cure unevenly. Careful handling at this stage prevents mechanical bruising, which can trigger premature enzymatic browning and localized over-fermentation during the subsequent killing and sweating stages.

3.3 Postharvest handling

Immediately after harvest, green beans are aromatically rich flavour compounds present as bound glucosides and require prompt, correctly sequenced processing; delays or poor interim storage (temperature, humidity, ventilation) before curing begins can encourage microbial contamination and uneven enzymatic activity (Havkin-Frenkel and Frenkel, 2006). Handling conditions at this stage are one of five recognized determinants of final cured-bean quality, alongside genetic profile, growing conditions, curing-process conditions, and the eventual balance of aromatic compounds (Dunphy and Bala, 2011, Van Dyk *et al.*, 2010).

3.4 Conventional processing (curing) techniques

Curing follows four classical stages such as killing (hot-water immersion at 60–70°C for about 3 minutes, or brief boiling at 93–96°C, to rupture cell structure and allow enzyme–substrate contact), sweating (24–48 hours in warm, humid, airtight conditions; prolonging this stage risks rot), sun drying alternated with sweating over several weeks, and conditioning (extended storage for aroma stabilisation) (Havkin-Frenkel & Frenkel, 2006; Odoux and Grisoni, 2011). The killing step is decisive: its temperature and duration directly determine the extent of enzymatic breakdown of glucovanillin to free vanillin, and specific pretreatments have been shown experimentally to shorten the overall curing period without compromising vanillin yield (Sreedhar *et al.*, 2007). Because none of these stages can compensate for a harvest made at the wrong maturity stage, maturity indexing, careful harvesting and controlled curing together rather than any single step decide whether a lot achieves premium-grade aroma and vanillin content.

4. MANAGEMENT OF PRE- AND POST-HARVEST FACTORS

4.1 Climate-smart cultivation under trellis-based dome and low-cost vanilla units

The CUTM geodesic dome and companion low-cost naturally-ventilated polyhouse address root-zone and canopy stress simultaneously consisting soilless media control waterlogging and *Fusarium* risk, while the modular rotary trellis ensures uniform diffused-light distribution across vines, and IoT-linked sensors (temperature, RH, CO_2, substrate moisture) convert the structure into a responsive rather than passive system. Maintaining sensor-guided set points (25–35°C, 75–80% RH, 350–400 ppm CO_2, 60–75% field capacity) directly targets the abiotic drivers of *VpPAL1* expression and vanillin biosynthesis identified above (Fock-Bastide *et al.*, 2014; Pradhan *et al.*, 2024).

4.2 Good Agricultural Practices (GAP)

Disease-free planting material, correct spacing, vine training/looping, shade regulation and mulching remain the foundation of consistent yield and reduce the "environment" stresses on plant expression (Anandaraj *et al.*, 2005; Reddy and Shukla, 2007). GAP protocols standardize pollination timing (6 am–1 pm effective window) and fruit-load control (5–6 flowers/inflorescence, 10–12 inflorescences/vine), both shown to influence pod-set consistency and quality (Van Dyk *et al.*, 2024).

4.3 Organic disease management

Trichoderma viride/harzianum root-dip or substrate-drench application, *Bacillus subtilis* and *Pseudomonas fluorescens* as antagonists, and neem-based botanicals alternated with copper fungicides together suppress *Fusarium* and associated pathogens without synthetic residues, consistent with the crop's traditionally organic cultivation status in India (Reddy *et al*., 2022; Francis, 2006).

4.4 Proper harvesting and handling

Harvest timed strictly to the tip-yellowing maturity index, individual hand-cutting, and prompt, sorted transfer to curing minimise the two irreversible quality losses — immature-bean aroma deficiency and over-ripe splitting identified as key determinants of final grade (Van Dyk *et al*., 2014).

4.5 Advanced processing techniques

4.5.1 Enzyme-Assisted Curing

Conventional curing converts less than 2% of the 10–15% glucovanillin present in green beans to free vanillin, since glucovanillin and β-glucosidase are spatially separated within the pod (Ranadive, 2011, as cited in vanilla curing literature). Exogenous cellulase, pectinase and β-glucosidase, combined with pre-freezing/thawing to break cellular compartmentation, have raised vanillin yield to 4.25–7.0% (dry weight) and shortened curing time (Zhang et al., 2014). High hydrostatic pressure (HHP, 50–600 MPa) similarly increases β-glucosidase activity and vanillin content as a non-thermal killing alternative (Buitimea-Cantúa *et al*., 2022).

4.5.2 Ultrasound/Microwave-Assisted Extraction

Ultrasound and microwave pretreatment accelerate cell-structure disruption, shortening curing/extraction time; however, excessive sonication (>15 min) can inactivate β-glucosidase and reduce final vanillin yield, indicating a treatment-intensity optimum (Antonio-Gutiérrez *et al*., 2023).

4.5.3 Solar and Low-Energy Drying

Traditional sun-drying alternated with sweating remains the dominant low-energy method, but near-infrared (NIR) monitoring of moisture and firmness during drying is emerging as a non-destructive tool to standardise this stage and reduce over/under-drying losses on a commercial scale (Lalanne-Tisné *et al*., 2025).

4.5.4 Biotechnological Vanillin Production

Given that natural bean-derived vanillin cannot meet global demand, microbial/fermentation routes using ferulic acid or eugenol (from agro-waste such as rice bran, groundnut shell, or banana peel) via engineered *E. coli*, *Pseudomonas*, and fungal systems are scaling as "natural-status" alternatives, with *E. coli* platforms reported to yield up to 38.3 g/L (Saeed *et al*., 2021; Gallage *et al*., 2014).

4.5.5 Waste Minimisation and By-Product Utilisation

Agro-industrial residues such as rice bran, groundnut shell, coir pith, banana peel that serve as low-cost ferulic-acid/vanillin precursor substrates for solid-state and submerged fermentation, converting what would otherwise be waste into a value stream (Gadhe *et al.,* 2011; Rejani and Radhakrishnan, 2022; Saeed *et al*., 2021).

4.5.6 Value-Added Products from Vanilla

Beyond whole cured beans, vanilla is processed into oleoresin, extract, and encapsulated powder forms; microencapsulation by complex coacervation/spray-drying (chitosan–gum arabic wall material) has achieved >84% retention efficiency, addressing vanillin's instability to oxygen, light and humidity.

4.5.7 Quality Assurance and Authentication

Because natural vanillin commands a large price premium over synthetic, adulteration is a persistent industry problem; Site-Specific Natural Isotope Fractionation NMR (SNIF-NMR) and compound-specific isotope-ratio mass spectrometry ($\delta^{13}C$, $\delta^{2}H$ via GC-IRMS) are the established gold-standard tools for distinguishing natural bean-derived vanillin from synthetic or bio-fermented sources and for geographic-origin verification (Remaud *et al*., 1997; Guyader *et al*., 2019).

4.5.8 Analytical Methods

Routine quality and process monitoring relies on HPLC for phenolic/vanillin quantification, GC-MS/GC-olfactometry for aroma-compound profiling, and spectrophotometric assays for β-glucosidase activity, complemented by emerging non-destructive NIR spectroscopy for in-line moisture and maturity assessment (Pérez-Silva *et al*., 2006; Lalanne-Tisné *et al*., 2025).

5. CONCLUSION

This study presents an integrated, climate-smart framework for precision vanilla cultivation that highlighted the entire production chain starting from soilless, IoT-monitored, trellis-based protected cultivation through organic disease and nutrient management, to precise pollination, maturity-indexed harvesting, and advanced curing and processing. Biotic pressure, chiefly *Fusarium oxysporum*, and abiotic stressors (temperature, humidity, CO_2, water and root-zone EC) were identified as the two dominant constraints on both yield and vanillin biosynthesis, while phosphorus and micronutrient management emerged as key levers for growth and flavour-compound accumulation. On the postharvest side, correct maturity indexing and controlled curing were shown to be irreplaceable determinants of final quality, with emerging techniques like enzyme- and pressure-assisted curing, ultrasound/microwave pretreatment, NIR-monitored drying, biotechnological vanillin production, and isotope-based authentication offering pathways to improve yield, consistency and market trust. Collectively, the CUTM vanilla dome and low-cost unit demonstrate that this integrated model is technically feasible at both research and smallholder-adjacent scale, positioning precision, protected, organic vanilla cultivation as a viable and climate-resilient direction for expanding India's and particularly Odisha's share of global natural vanilla and vanillin production.

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