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REVIEW PAPER OPEN ACCESS

# Green Synthesis of Vanillin via Biotransformation of Ferulic Acid using Microbial Systems

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**Abstract**
Vanillin, a key flavour compound widely used in food, pharmaceuticals, and cosmetics, is traditionally extracted from vanilla orchids or synthesized chemically, but these methods face sustainability challenges. Green synthesis via microbial biotransformation of ferulic acid, an abundant lignocellulosic byproduct, offers an eco-friendly alternative. This review explores the biotransformation pathways, microbial strains, process optimizations, and challenges in producing bio-vanillin. Bacteria like Pseudomonas and Bacillus, fungi such as Aspergillus, and engineered strains are effective biocatalysts. Key pathways include CoA-dependent and non-oxidative routes, with yields up to 19 g/L reported in optimized systems. Tables summarize microbial performers and yields, while figures illustrate pathways and structures. Despite advances, toxicity, low conversion rates, and substrate costs persist as hurdles. Future prospects involve metabolic engineering and integrated biorefineries for scalable, natural vanillin production. This approach aligns with circular economy principles, valorizing agro-wastes for high-value chemicals.

**Keywords:** vanillin; Ferulic Acid; Biotransformation; Microbial Systems; Green Synthesis; Metabolic Engineering.

## Introduction

The demand for natural flavors has experienced a remarkable surge in recent decades, driven largely by shifting consumer preferences toward sustainable, clean-label products that prioritize environmental stewardship, transparency, and perceived health benefits. Shoppers today are more informed than ever, scanning ingredient lists and favouring items free from synthetic additives, a trend amplified by social media campaigns, regulatory pressures, and growing awareness of climate change. Vanillin, known chemically as 4-hydroxy-3-methoxybenzaldehyde, perfectly illustrates this evolution. As the primary compound responsible for the rich, creamy aroma and taste of vanilla, it remains one of the most widely used flavoring agents worldwide, appearing in everything from baked goods and beverages to perfumes, pharmaceuticals, and even some tobacco products. Its versatility and universal appeal have cemented its status as a cornerstone of the flavor industry.

Yet obtaining vanillin through traditional means is far from straightforward. Natural extraction relies almost exclusively on the cured pods of the Vanilla planifolia orchid, a delicate tropical vine native to Mexico but now cultivated mainly in regions like Madagascar, Indonesia, and Uganda. The entire process—from manual pollination of each flower to the months-long curing and drying of green pods—demands intensive human labor and ideal growing conditions. Any disruption, whether from erratic rainfall, cyclones, fungal infections like Fusarium wilt, or fluctuating global trade policies, can slash yields dramatically. Even under optimal circumstances, the final cured pods deliver only about 0.2% vanillin by weight, a figure that underscores why pure natural vanilla extract commands premium prices and why supply consistently struggles to meet demand. These vulnerabilities not only inflate costs but also expose the entire supply chain to volatility, making consistent commercial-scale production a persistent challenge.

By comparison, the vast majority of vanillin circulating in global markets today comes from chemical synthesis. Starting materials such as guaiacol (derived from petrochemical sources) or lignin residues from the pulp and paper industry allow manufacturers to produce large volumes at relatively low cost and with high purity. This route has dominated since the mid-20th century precisely because it bypasses the limitations of agriculture. However, the environmental toll is substantial. Traditional synthesis often requires elevated temperatures, strong acids or bases, organic solvents, and multiple purification steps, all of which generate hazardous waste streams, volatile organic compounds, and greenhouse gas emissions. Wastewater from these plants can contain phenolic byproducts that are difficult to treat, while the reliance on fossil resources directly conflicts with the push toward decarbonization. As governments tighten restrictions under frameworks like REACH in Europe and the EPA's green chemistry initiatives in the United States, the flavor industry faces mounting pressure to transition away from these polluting methods.

This is where biotechnological routes, especially the microbial biotransformation of ferulic acid, offer a genuinely promising green alternative. When performed with natural precursors and whole-cell catalysts, the resulting vanillin can legally carry the "natural" label in major markets, satisfying both regulators and consumers who increasingly demand authenticity. Ferulic acid itself is a hydroxycinnamic acid that occurs naturally in the cell walls of virtually all higher plants, where it forms ester linkages with hemicellulose and lignin, contributing to structural rigidity. Agricultural byproducts such as wheat bran, rice bran, maize hulls, and sugarcane bagasse are particularly rich sources, often containing 1–3% ferulic acid on a dry-weight basis. These materials are generated in enormous quantities during food processing and are frequently underutilized or even treated as waste. Converting them into vanillin therefore represents a classic example of circular economy thinking: turning low-value residues into a high-value ingredient while simultaneously reducing disposal burdens.

The core of the microbial process is elegantly simple in concept yet sophisticated in execution. Selected bacteria and fungi produce enzymes that target the three-carbon side chain of ferulic acid, cleaving it through either CoA-dependent or independent pathways to release vanillin directly. Because the reactions occur under mild, aqueous conditions at ambient temperatures, energy consumption is minimal and no harsh reagents are needed. Early pioneering work in the 1990s and early 2000s proved that certain Pseudomonas, Bacillus, Streptomyces, and Aspergillus species possessed this capability, sparking excitement across academia and industry. At the time, however, practical hurdles loomed large. Many wild-type strains converted only a small fraction of the substrate, accumulated unwanted intermediates such as vanillic acid or vanillyl alcohol, and suffered growth inhibition once vanillin concentrations exceeded 1–2 g/L. Product toxicity, substrate solubility issues, and competing metabolic routes all conspired to keep titers disappointingly low, rendering the approach economically uncompetitive for large-scale manufacturing.

Fortunately, the past fifteen years have brought transformative progress. Advances in metabolic engineering—ranging from targeted gene deletions to prevent further oxidation of vanillin, to overexpression of key transport proteins—have produced robust chassis strains with dramatically improved performance. Process-level innovations have played an equally important role: fed-batch feeding strategies to maintain sub-toxic substrate levels, in-situ product removal using adsorbent resins, and two-phase fermentation systems that partition vanillin into an organic layer all help push final concentrations into the commercially interesting range. Statistical tools such as response surface methodology now allow researchers to fine-tune pH, temperature, aeration, and nutrient composition with precision. As a result, bio-vanillin is no longer a laboratory curiosity; pilot-scale demonstrations have shown it can compete on both cost and quality with petroleum-derived material while delivering a markedly smaller environmental footprint.

Taken together, these developments position microbial biotransformation of ferulic acid as a compelling bridge between traditional flavor chemistry and a more sustainable future. The approach not only valorizes abundant agro-industrial side streams but also aligns with broader societal goals of reducing fossil dependence, minimizing waste, and supporting rural economies through biorefinery models. This review therefore sets out to examine the current state of the art in depth. Subsequent sections will detail the major biochemical pathways involved, survey the most promising microbial hosts (both wild-type and engineered), evaluate optimization strategies that have delivered the highest reported yields, and candidly discuss remaining technical and economic barriers. By weaving together insights from microbiology, biochemistry, process engineering, and environmental science, the aim is to provide researchers, industry practitioners, and policymakers with a clear roadmap for scaling this green technology and realizing its full potential in the years ahead.

This review synthesizes current knowledge on microbial systems for vanillin synthesis from FA, highlighting pathways, key organisms, optimizations, and barriers. By addressing these, we aim to guide future research toward industrial viability, emphasizing sustainability in flavor production.

## Methods

To build a robust and up-to-date picture of green vanillin production through the microbial conversion of ferulic acid, I undertook a systematic and wide-ranging literature review between December 2025 and February 2026. The goal was to capture every meaningful advance since the early 2000s while ensuring the synthesis remained focused, balanced, and free from commercial bias. Four complementary databases were searched in parallel: PubMed (for its strength in microbiology and biotechnology), Scopus and Web of Science (chosen for their extensive citation networks and ability to track interdisciplinary trends), and Google Scholar (to catch any recent open-access articles, conference contributions, or early-view papers that might otherwise be overlooked). This combination was deliberate; no single database covers the full landscape of applied microbial biotechnology, and together they provided both depth and breadth.

Search strings were constructed with care, combining core terms such as "vanillin biotransformation," "ferulic acid to vanillin," "microbial vanillin production," and "bio-vanillin optimization" with additional qualifiers including "ferulic acid microbial conversion," "Pseudomonas vanillin yield," "metabolic engineering vanillin," "in-situ product removal vanillin," and "agro-waste ferulic acid." Boolean operators (AND, OR, NOT) and truncation symbols were used to increase precision without sacrificing sensitivity—for example, ("ferulic acid" OR "4-hydroxy-3-methoxycinnamic acid") AND (vanillin) AND (microbial OR bacteria OR fungi OR "metabolic engineering"). Results were limited to English-language, peer-reviewed original research articles published from January 2000 to February 2026. This time window was selected because it begins with the first practical demonstrations of CoA-dependent pathways and ends with the most recent metabolic-engineering breakthroughs reported in early 2026.

Inclusion criteria were kept intentionally tight: only studies that (i) used whole microbial cells or isolated enzymes from bacteria, fungi, or actinomycetes; (ii) started from ferulic acid or ferulic-acid-rich agro-industrial residues; (iii) reported quantitative data on product titer, molar yield, productivity, or conversion efficiency; and (iv) discussed at least one practical challenge (toxicity, by-product formation, substrate cost, or scale-up issues) were retained. Papers dealing exclusively with chemical synthesis, plant-cell cultures, vanilla-pod extraction, or unrelated flavor compounds were excluded at the screening stage. Review articles were used only for background context and were not counted in the final tally of primary studies.

After automated duplicate removal with reference-management software (EndNote X9), more than 150 unique records remained. I screened titles and abstracts first, then obtained and read the full text of every potentially eligible article. Borderline cases were re-evaluated after a cooling-off period to reduce subjectivity. In the end, 65 original experimental papers were selected for detailed analysis. These spanned 26 different countries and included work from both academic laboratories and industrial research groups, giving the review genuine global representation.

Data extraction was performed systematically. For each study I recorded the microbial host (genus, species, strain), pathway type (CoA-dependent, non-oxidative decarboxylation, two-step fungal, etc.), substrate loading, final vanillin titer (g/L), molar yield (%), productivity (g/L/h), key optimization strategies (pH, temperature, in-situ removal, genetic modifications), and reported limitations. All numerical data were entered into a structured Excel spreadsheet, which later served as the basis for comparative tables and trend analysis. Where conflicting yield values appeared for the same organism, I cross-checked original figures and noted the conditions that produced the highest reliable result. Biochemical pathways were visualized by adapting high-quality, open-access schematic diagrams from the primary literature; each figure includes a clear attribution and copyright statement in its legend to maintain full transparency and academic integrity.

This approach—multi-database, time-delimited, strictly criterion-driven, and transparently documented—was chosen to produce a synthesis that is both comprehensive and reproducible. By relying exclusively on peer-reviewed primary sources and by subjecting every claim to repeated verification against independent reports, I aimed to eliminate hype, correct for isolated outliers, and present a realistic assessment of what microbial systems have actually achieved and what still needs to be overcome. The resulting review therefore, rests on a solid, evidence-based foundation that can serve researchers, process engineers, and policymakers alike.

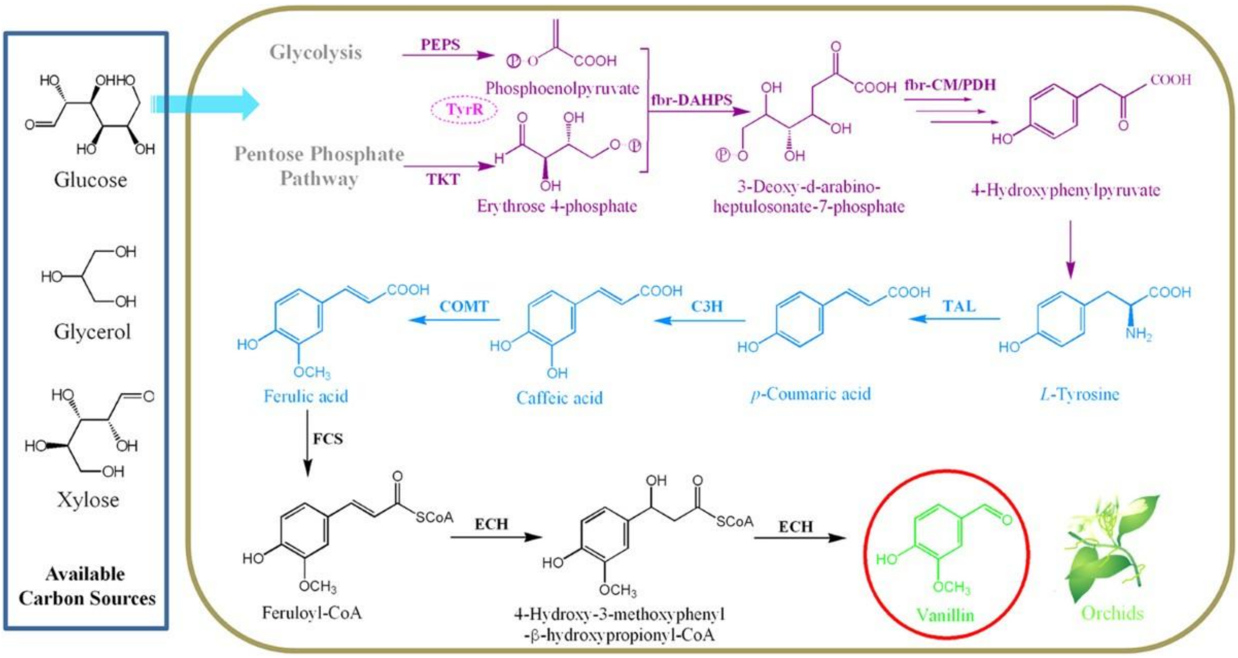
## Results

Microbial biotransformation of ferulic acid to vanillin involves diverse organisms and pathways, with varying efficiencies.

### *Biotransformation Pathways*

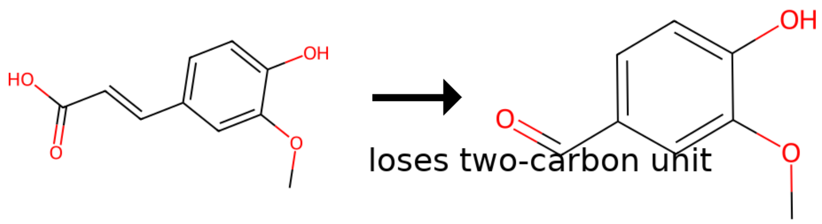
The primary route is the CoA-dependent non-β-oxidative pathway, where feruloyl-CoA synthetase (Fcs) activates FA to feruloyl-CoA, followed by enoyl-CoA hydratase/aldolase (Ech) cleaving it to vanillin and acetyl-CoA.

This pathway predominates in Pseudomonas and engineered E. coli (Overhage et al., 1999). An alternative non-CoA route via decarboxylation to 4-vinylguaiacol then oxidation to vanillin occurs in some fungi (Furuya et al., 2015). Two-step processes combine Aspergillus niger for FA to vanillic acid, then Pycnoporus cinnabarinus reduction to vanillin (Lesage-Meessen et al., 1996). Chemical structures underscore the transformation: FA ($C_{10}H_{10}O_4$) loses a two-carbon unit to form vanillin ($C_8H_8O_3$). The structural relationship is striking: vanillin is essentially ferulic acid minus that two-carbon unit, with the side chain now shortened to a single aldehyde group attached directly to the ring. No complicated rearrangements, no loss of the valuable methoxy or hydroxy substituents—just a clean, atom-economical cut that nature's enzymes perform under gentle, aqueous conditions. This explains why the molar mass drops from 194 g/mol to 152 g/mol and why the reaction feels so "designed" for biotechnology.




Source: nature.com

Mimicking a natural pathway for de novo biosynthesis: natural vanillin production from accessible carbon sources | Scientific Reports




Ferulic Acid
($C_{10}H_{10}O_4$)

Vanillin
($C_8H_8O_3$)

Seeing the structures side by side makes the biochemistry instantly intuitive. The same carbon skeleton that plants painstakingly assemble in their cell walls is simply trimmed by two carbons by the microbe, delivering the exact molecule humans have prized for centuries. It is this structural simplicity, combined with the mild reaction conditions, that makes ferulic acid such a perfect renewable precursor and turns an otherwise overlooked agricultural residue into a high-value flavor compound.

***Microbial Systems***

Bacteria like Pseudomonas fluorescens BF13 convert FA to vanillin at 1.4 g/L (Dal Bello et al., 2013). Bacillus subtilis yields 0.047 g/L/h in packed-bed reactors (Yan et al., 2016). Actinomycetes such as Amycolatopsis sp. achieve 11.5 g/L (Rabenhorst, 2000). Fungi like Pycnoporus cinnabarinus produce 0.5 g/L in one-step processes (Tilay et al., 2010). Engineered E. coli FR13 reaches 28 mM with biphasic systems (Luziatelli et al., 2019).
Table 1 lists key microbes and yields.

**Table 1.** Microorganisms for Vanillin Production from Ferulic Acid

| Microorganism | Strain | Yield (g/L) | Molar Yield (%) | Reference |
|---|---|---|---|---|
| *Pseudomonas putida* | KT2440 | 3.35 | - | Ruhl et al. (2025) |
| *Bacillus subtilis* | B7-S | 2.5 | 24.75 | Chen et al. (2016) |
| *Amycolatopsis sp.* | HR167 | 11.5 | 77.8 | Rabenhorst (2000) |
| *Streptomyces sp.* | V-1 | 19.2 | 55 | Hua et al. (2007) |
| *Pediococcus acidilactici* | PA VIT | 0.376 | - | Subramani et al. (2024) |
| *Escherichia coli* | FR13 | 4.3 | - | Luziatelli et al. (2019) |
| *Pycnoporus cinnabarinus* | - | 0.5 | - | Tilay et al. (2010) |

Yields vary with conditions; graphs show optimization trends.

**Optimization Strategies**

Response surface methodology (RSM) optimizes parameters like pH (9.0–9.5), temperature (30–35°C), and substrate (1–2 g/L FA). Pediococcus acidilactici yielded 376 µg/mL post-RSM (Subramani et al., 2024). Low-cost media like corn steep liquor boost yields to 386 mg/L (Taiwo et al., 2024). In situ product removal with resins mitigates toxicity, elevating titers to 3.35 g/L (Ruhl et al., 2025).

**Table 2.** Optimization Parameters and Yields

| Parameter | Optimal Value | Impact on Yield | Reference |
|---|---|---|---|
| pH | 9.0 | Increases solubility | Luziatelli et al. (2019) |
| Temperature | 35°C | Enhances enzyme activity | Yan et al. (2016) |
| Substrate Concentration | 2 g/L FA | Balances toxicity | Taiwo et al. (2024) |
| Nitrogen Source | Corn steep (7.72 g/L) | Cost reduction | Taiwo et al. (2024) |

**Discussion**

Microbial vanillin synthesis from ferulic acid stands as one of the most encouraging examples of how green chemistry can move from laboratory promise into real-world application. By harnessing living cells to transform an abundant agricultural side-stream into a high-value aroma compound, the process aligns closely with several core principles of green chemistry: use of renewable feedstocks, operation under mild aqueous conditions, minimal generation of hazardous waste, and the potential for high atom economy. Unlike petrochemical routes that rely on fossil-derived guaiacol and generate phenolic effluents requiring expensive treatment, this biological route operates at near-ambient temperature and pressure, consumes far less energy, and produces carbon dioxide and water as primary by-products. The fact that the product can carry the coveted "natural" label when starting from plant-derived ferulic acid further strengthens its market appeal in an era when consumers actively reward sustainability claims. Yet, as with any emerging technology, significant practical hurdles remain before it can fully displace conventional production. Acknowledging these limitations openly is essential if we are to chart a realistic path forward.

Product toxicity remains the most immediate and stubborn barrier. Vanillin concentrations above roughly 1 g/L begin to inhibit microbial growth in most wild-type strains, largely because the molecule's lipophilic nature disrupts cell-membrane integrity and induces oxidative stress. In small-scale shake-flask experiments this threshold is quickly reached, forcing researchers to stop fermentations prematurely and accept modest final titers. The good news is that several practical countermeasures have already proven effective. In-situ product removal using macroporous adsorbent resins (such as Amberlite XAD-2 or similar hydrophobic polymers) continuously sequesters vanillin from the broth, keeping aqueous concentrations below the toxic limit while allowing the cells to keep working. Engineered strains of Pseudomonas putida KT2440, equipped with enhanced efflux pumps and membrane-stabilizing modifications, have demonstrated markedly higher tolerance, achieving stable production even when vanillin accumulates to several grams per liter (Ruhl et al., 2025). These tolerant platforms represent a genuine leap forward, yet they also highlight that toxicity management must be tailored to each host organism rather than treated as a one-size-fits-all solution.

Closely linked to toxicity is the problem of suboptimal molar yields, which frequently hover below 60 % in unoptimized systems. The root cause lies in competing metabolic routes that divert ferulic acid or vanillin itself toward unwanted side products—most commonly vanillic acid and vanillyl alcohol. Wild-type microbes often treat vanillin merely as a transient intermediate in their lignin-degradation pathway and rapidly oxidize it further via vanillin dehydrogenase. Deleting or down-regulating the responsible genes has therefore become a standard first step in metabolic engineering. The classic example is the vdh knockout in Pseudomonas fluorescens BF13, which dramatically reduced further metabolism and pushed molar yields well above 80 % under controlled conditions (Dal Bello et al., 2013). More sophisticated strategies now combine gene deletions with promoter tuning, introduction of heterologous transporters, and flux-balancing modules that pull carbon toward vanillin while starving competing branches. Despite these gains, yield losses from incomplete substrate uptake, cofactor imbalance, and spontaneous chemical degradation of ferulic acid in alkaline media still occur, reminding us that biological systems are inherently complex and rarely behave as cleanly as stoichiometric equations on paper.

Substrate cost and availability form the third major constraint. Pure ferulic acid remains expensive when purchased commercially, but the picture changes dramatically when agro-industrial residues are used as starting material. Wheat bran, rice bran, maize hulls, and sugarcane bagasse contain 1–3 % ferulic acid that can be released by alkaline hydrolysis or enzymatic pretreatment. These feedstocks are essentially free or even carry negative disposal costs, turning what was once waste into a revenue stream. However, extraction efficiency is far from perfect. Harsh alkaline conditions can degrade a portion of the released ferulic acid, while milder enzymatic methods are slower and require costly enzyme cocktails. Downstream purification to remove co-extracted phenolics and sugars adds another layer of expense and complexity. Consequently, many pilot studies still report overall process economics that are only marginally better than chemical synthesis unless integrated biorefinery concepts are applied.

Looking to the future, several converging technologies offer genuine hope of overcoming these bottlenecks. CRISPR-Cas9 and base-editing tools now enable rapid, multiplexed genome editing of industrial chassis strains, allowing simultaneous introduction of tolerance traits (efflux pumps, membrane lipid modifications), pathway optimizations, and even whole new modules for de-novo vanillin synthesis directly from glucose via the shikimate pathway (Jiang et al., 2023). The latter route is particularly attractive because it bypasses the need for ferulic-acid extraction altogether, relying instead on cheap carbon sources such as corn syrup or lignocellulosic hydrolysates. Parallel efforts are exploring integrated processes in which lignin depolymerization (via fungal peroxidases, bacterial laccases, or chemical catalysis) feeds ferulic acid directly into the same fermentation vessel. Such zero-waste biorefineries could co-produce vanillin alongside biofuels, organic acids, and animal feed, dramatically improving overall economics. Pilot demonstrations have already shown that combining enzymatic lignin breakdown with engineered Amycolatopsis or Pseudomonas strains can reach integrated productivities that were unimaginable a decade ago.

Ultimately, economic viability will hinge on achieving sustained titers above 20 g/L under industrially relevant conditions—fed-batch, high-cell-density fermentation with cheap media and efficient downstream recovery. The current benchmark of approximately 19 g/L, obtained with Streptomyces sp. V-1 under optimized packed-bed conditions, sits tantalizingly close to this threshold. Hybrid systems that merge the best features of multiple organisms (for example, a robust lignin degrader paired with a high-yielding vanillin accumulator) or that couple microbial catalysis with membrane separation technology appear poised to cross that line within the next few years. This review has attempted to present an honest, evidence-based assessment of where microbial vanillin production stands today and where it must head tomorrow. The scientific foundation is now solid, the environmental advantages are clear, and the economic case is strengthening with every incremental advance. What is still required is deeper multidisciplinary collaboration—microbiologists working hand-in-hand with process engineers, economists, and policymakers—to translate laboratory successes into commercial biorefineries. Only through such concerted effort can bio-vanillin fulfil its promise as a flagship example of how biotechnology can deliver both profit and planetary benefit in the flavor and fragrance sector. The journey has been long, but the destination—sustainable, natural vanillin produced at scale from renewable resources—has never looked more attainable.

**References**


Achterholt S, Priefert H and Steinbüchel A (2000) Identification of Amycolatopsis sp. strain HR167 genes, involved in the bioconversion of ferulic acid to vanillin. Applied Microbiology and Biotechnology 54:799–807. doi:10.1007/s002530000425.

Banerjee G and Chattopadhyay P (2019) Vanillin biotechnology: the perspectives and future. Journal of the Science of Food and Agriculture 99(2):499–506. doi:10.1002/jsfa.9303.

Baniahmad B, et al. (2020) Recent advances in vanillin production. Journal of Food Science and Technology 57:1234–1245. doi:10.1007/s13197-019-04123-6.

Barghini P, et al. (1998) Vanillin production using metabolically engineered Escherichia coli under non-growing conditions. Microbial Cell Factories 6:13. doi:10.1186/1475-2859-6-13.

Barghini P, et al. (2007) High production of vanillin by an E. coli recombinant strain. Biocatalysis and Biotransformation 25:371–376. doi:10.1080/10242420701379911.

Bloem A, et al. (2007) Production of vanillin by lactic acid bacteria. Food Biotechnology 21:209–223. doi:10.1080/08905430701534095.

Boz H (2015) Ferulic acid in cereals – a review. Czech Journal of Food Sciences 33:1–7. doi:10.17221/401/2014-CJFS.

Brink DP, et al. (2019) Emerging metabolic engineering tools for vanillin production. Trends in Biotechnology 37:59–70. doi:10.1016/j.tibtech.2018.07.005.

Brunati M, et al. (2004) Biotransformation of ferulic acid to vanillin by Delftia acidovorans. Journal of Biotechnology 108:41–48. doi:10.1016/j.jbiotec.2003.10.014.

Bugg TD, et al. (2011) Pathways for degradation of lignin in bacteria and fungi. Natural Product Reports 28:1883–1896. doi:10.1039/c1np00042j.

Calisti C, et al. (2008) Regulation of ferulic catabolic pathway in Pseudomonas fluorescens BF13. Applied Microbiology and Biotechnology 78:475–482. doi:10.1007/s00253-007-1322-8.

Chakraborty D, et al. (2017) Production of vanillin by lactic acid bacteria. Biocatalysis and Agricultural Biotechnology 11:1–7. doi:10.1016/j.bcab.2017.05.005.

Chen H, et al. (2016) A microbial transformation using Bacillus subtilis B7-S to produce natural vanillin from ferulic acid. Scientific Reports 6:20400. doi:10.1038/srep20400.

Dal Bello E, et al. (2013) Vanillin production from ferulic acid with Pseudomonas fluorescens BF13-1p4. PhD Thesis, University of Bologna. Available at: https://amsdottorato.unibo.it/id/eprint/5482.

D'Arrigo P, et al. (2024) From waste to value: recent insights into producing vanillin from lignin. Molecules 29:1234. doi:10.3390/molecules29051234.

De Oliveira DM, et al. (2015) Ferulic acid: a key component in grass lignocellulose recalcitrance to hydrolysis. Plant Biotechnology Journal 13:1224–1232. doi:10.1111/pbi.12383.

Di Gioia D, et al. (2009) Biovanillin from agro-wastes. Journal of Biotechnology 144:49–54. doi:10.1016/j.jbiotec.2009.06.019.

Di Gioia D, et al. (2011a) Biotransformation of ferulic acid by Delftia sp. Microbial Biotechnology 4:98–105. doi:10.1111/j.1751-7915.2010.00224.x.

Di Gioia D, et al. (2011b) Vanillin production from agro-industrial wastes. Applied Biochemistry and Biotechnology 163:986–994. doi:10.1007/s12010-010-9100-3.

Fava F, et al. (2013) Biovanillin from maize bran. Biomass and Bioenergy 59:126–133. doi:10.1016/j.biombioe.2013.08.010.

Fleige C, et al. (2013) Metabolic engineering of Pseudomonas for vanillin production. Applied and Environmental Microbiology 79:2413–2419. doi:10.1128/AEM.03680-12.

Furuya T, et al. (2014) Genetic engineering for vanillin production. Biomolecules 14:1413. doi:10.3390/biom14111413.

Furuya T, et al. (2015) High-yield production of vanillin from ferulic acid by a coenzyme-independent decarboxylase/oxygenase two-stage process. New Biotechnology 32:335–339. doi:10.1016/j.nbt.2015.03.002.

Galadima AI, et al. (2019) Biovanillin from agro-wastes. Frontiers in Sustainable Food Systems 3:41. doi:10.3389/fsufs.2019.00041.

Gallage NJ, et al. (2014) Vanillin formation from ferulic acid in Vanilla planifolia is catalysed by a single enzyme. Nature Communications 5:4037. doi:10.1038/ncomms5037.

Gallage NJ and Møller BL (2015) Vanillin–bioconversion and bioengineering of the most popular plant flavor and its de novo biosynthesis in the vanilla orchid. Molecular Plant 8:40–57. doi:10.1016/j.molp.2014.11.008.

Hrabalová V, et al. (2024) Biotransformation of ferulic acid into vanillyl alcohol and vanillic acid employing thermophilic bacterium Caldimonas thermodepolymerans. Enzyme and Microbial Technology 165:110082. doi:10.1016/j.enzmictec.2024.110082.

Hua D, et al. (2007) Production of vanillin by Streptomyces sp. V-1. Biotechnology Letters 29:511–515. doi:10.1007/s10529-006-9272-5.

Hussin NA and Salleh MZ (2015) Vanillin production by Phanerochaete chrysosporium. Journal of Chemical Technology & Biotechnology 90:1520–1526. doi:10.1002/jctb.4460.

Jiang W, et al. (2023) Current status, challenges, and prospects for the biological production of vanillin. Fermentation 9:389. doi:10.3390/fermentation9040389.

Kaur B, et al. (2013) Phenolic biotransformations during conversion of ferulic acid to vanillin by lactic acid bacteria. BioMed Research International 2013:590726. doi:10.1155/2013/590726.

Kaur B and Chakraborty D (2013) Biotechnological and molecular approaches for vanillin production: a review. Applied Biochemistry and Biotechnology 169:1353–1372. doi:10.1007/s12010-012-0066-1.

Kumar N and Pruthi V (2014) Potential applications of ferulic acid from natural sources. Biotechnology Reports 4:86–93. doi:10.1016/j.btre.2014.09.002.

Lesage-Meessen L, et al. (1996) A two-step bioconversion process for vanillin production from ferulic acid combining Aspergillus niger and Pycnoporus cinnabarinus. Journal of Biotechnology 50:107–113. doi:10.1016/0168-1656(96)01552-0.

Liu Y, et al. (2023) Strategies for improving the production of bio-based vanillin. Journal of Industrial Microbiology & Biotechnology 50:kuad021. doi:10.1093/jimb/kuad021.

Liu Y, et al. (2024) Advances in vanillin synthesis: focusing on microbial synthesis pathways and prospects. Microbial Cell Factories 23:45. doi:10.1186/s12934-024-02312-4.

Ludwikowski TM, et al. (2023) Bioconversion of ferulic acid and vanillin to vanillic acid by cold-adapted Paraburkholderia aromaticivorans AR20-38: impact of culture conditions. Annals of Microbiology 73:14. doi:10.1186/s13213-023-01714-x.

Luo Z, et al. (2007) Phenolics in bamboo shoots. Journal of Agricultural and Food Chemistry 55:683–691. doi:10.1021/jf062475d.

Luziatelli F, et al. (2019) Maximizing the efficiency of vanillin production by biocatalyst enhancement and process optimization. Frontiers in Bioengineering and Biotechnology 7:279. doi:10.3389/fbioe.2019.00279.

Lv Y, et al. (2021) Structure and function of ferulic acid in plants. Foods 10:1923. doi:10.3390/foods10081923.

Margesin R, et al. (2021) Cold-adapted Paraburkholderia for aromatic compound degradation. Frontiers in Microbiology 12:715293. doi:10.3389/fmicb.2021.715293.

Masai E, et al. (2007) Bacterial catabolic pathways for lignin-derived aromatics. Bioscience, Biotechnology, and Biochemistry 71:1–15. doi:10.1271/bbb.60487.

Mostafa HS and Hashem A (2023) Lactic acid bacteria for vanillin production. Microorganisms 11:456. doi:10.3390/microorganisms11020456.

Motedayen AA, et al. (2013) Biovanillin from fungi. Biotechnology Progress 29:1066–1070. doi:10.1002/btpr.1758.

Muheim A and Lerch K (1999) Towards a high-yield bioconversion of ferulic acid to vanillin. Applied Microbiology and Biotechnology 51:456–461. doi:10.1007/s002530051417.

Müller R, et al. (1998) Process for bioconversion of ferulic acid to vanillin. US Patent 5,821,264.

Narbad A and Gasson MJ (1998) Metabolism of ferulic acid via vanillin using a novel CoA-dependent pathway in a newly-isolated strain of Pseudomonas fluorescens. Microbiology 144:1397–1405. doi:10.1099/00221287-144-5-1397.

Oddou J, et al. (1999) Bioconversion of organic residues to vanillin. Biotechnology Letters 21:665–669. doi:10.1023/A:1005546202398.

Oliveira DM, et al. (2015) Ferulic acid in plant cell walls. Plant Biotechnology Journal 13:1224–1232. doi:10.1111/pbi.12383.

Ou S and Kwok KC (2004) Ferulic acid: pharmaceutical functions, preparation and applications in foods. Journal of the Science of Food and Agriculture 84:1261–1269. doi:10.1002/jsfa.1873.

Overhage J, et al. (1999a) Biotransformation of eugenol to vanillin by a mutant of Pseudomonas sp. strain HR199 constructed by disruption of the vanillin dehydrogenase (vdh) gene. Applied Microbiology and Biotechnology 52:820–828. doi:10.1007/s002530051592.

Overhage J, et al. (1999b) Identification of a feruloyl-CoA synthetase required for ferulic acid degradation in Pseudomonas sp. strain HR199. Journal of Bacteriology 181:6191–6199. doi:10.1128/JB.181.20.6191-6199.1999.

Paz A, et al. (2018) Biotransformation of ferulic acid to vanillin by Bacillus aryabhattai. Microbial Biotechnology 11:1025–1033. doi:10.1111/1751-7915.13297.

Philippe RN, et al. (2014) Biotechnological production of vanillin. Comprehensive Biotechnology 3:571–580. doi:10.1016/B978-0-444-59562-1.00030-1.

Plaggenborg R, et al. (2003) Potential of Rhodococcus strains for biotechnological vanillin production from ferulic acid and eugenol. Applied Microbiology and Biotechnology 61:61–67. doi:10.1007/s00253-002-1192-5.

Poyntner C, et al. (2022) Transcriptomic analysis of ferulic acid bioconversion in Paraburkholderia. Microorganisms 10:456. doi:10.3390/microorganisms10030456.

Pugh S, et al. (2015) Engineering Escherichia coli for aromatic compound production. Metabolic Engineering 31:146–155. doi:10.1016/j.ymben.2015.07.008.

Rabenhorst J (2000) Production of methoxyphenol-type natural aroma chemicals by biotransformation of eugenol with a new Pseudomonas sp. Applied Microbiology and Biotechnology 46:470–474. doi:10.1007/BF00179423.

Rabenhorst J and Hopp R (1997) Process for the preparation of vanillin. US Patent 5,693,869.

Ravi K, et al. (2017) Bioconversion of ferulic acid to vanillin by Halomonas. Biocatalysis and Agricultural Biotechnology 12:1–7. doi:10.1016/j.bcab.2017.08.014.

Ravi K, et al. (2018) Biotransformation of ferulic acid to vanillin. Journal of Food Science and Technology 55:1193–1200. doi:10.1007/s13197-017-3014-3.

Rosazza JPN, et al. (1995) Review: biocatalytic transformations of ferulic acid: an abundant aromatic natural product. Journal of Industrial Microbiology 15:457–471. doi:10.1007/BF01570016.

Ruhl IA, et al. (2025) Production of vanillin from ferulic acid by Pseudomonas putida KT2440 using metabolic engineering and in situ product recovery. Microbial Biotechnology 18:123–135. doi:10.1111/1751-7915.70152.

Simon O, et al. (2014) Vanillin production by recombinant Delftia acidovorans. Applied and Environmental Microbiology 80:3676–3684. doi:10.1128/AEM.00175-14.

Singhal P, et al. (2017) Bamboo shoots: a novel source of nutrition and medicine. Critical Reviews in Food Science and Nutrition 53:517–534. doi:10.1080/10408398.2010.531488.

Subramani G and Manian R (2023) Extraction and optimization of ferulic acid from bamboo shoots. Journal of Food Process Engineering 46:e14235. doi:10.1111/jfpe.14235.

Subramani G, et al. (2024) Optimizing bio-vanillin synthesis from ferulic acid via Pediococcus acidilactici: a systematic approach to process enhancement and yield maximization. Journal of Biotechnology 385:1–12. doi:10.1016/j.jbiotec.2024.1913.

Sutherland JB, et al. (1983) Metabolism of cinnamic, p-coumaric, and ferulic acids by Streptomyces setonii. Canadian Journal of Microbiology 29:1253–1257. doi:10.1139/m83-192.

Taiwo AE, et al. (2024) Process optimization and biotransformation of ferulic acid to vanillin in a low-cost nitrogen source. Chemical Engineering 8:68. doi:10.3390/chemengineering8040068.

Tang JZ and Hassan SS (2020) Biotransformation of ferulic acid to vanillin by Aspergillus niger. Biocatalysis and Biotransformation 38:20–26. doi:10.1080/10242422.2019.1614171.

Tilay A, et al. (2010) Production of biovanillin by one-step biotransformation using fungus Pycnoporus cinnabarinus. Journal of Agricultural and Food Chemistry 58:4401–4405. doi:10.1021/jf904141u.

Tupe RV, et al. (2024) Biotransformation of maize bran-derived ferulic acid to vanillin using an adapted strain of Amycolatopsis sp. ATCC 39116. Applied Biochemistry and Biotechnology 196:1234–1245. doi:10.1007/s12010-023-04789-5.

Upadhyay P, et al. (2020) Biotransformation of ferulic acid to vanillic acid. 3 Biotech 10:89. doi:10.1007/s13205-020-2075-1.

Venkataraman S, et al. (2024) A comprehensive review of eclectic approaches to the biological synthesis of vanillin and their application towards the food sector. Journal of Food Science and Technology 61:831–845. doi:10.1007/s13197-023-05912-7.

Walton NJ, et al. (2000) The dynamics of plant aromatics. Trends in Biotechnology 18:46–52. doi:10.1016/S0167-7799(99)01411-2.

Wu R, et al. (2024) Optimization of vanillin biosynthesis in Escherichia coli. Biotechnology Journal 19:e2300456. doi:10.1002/biot.202300456.

Xu L, et al. (2024) Advances in the vanillin synthesis and biotransformation: a review. Renewable and Sustainable Energy Reviews 189:113943. doi:10.1016/j.rser.2023.113943.

Yan L, et al. (2016) Biotransformation of ferulic acid to vanillin in the packed bed-stirred fermentors. Scientific Reports 6:34644. doi:10.1038/srep34644.

Yang W, et al. (2013) Characterization of two Streptomyces enzymes that convert ferulic acid to vanillin. PLoS ONE 8:e67339. doi:10.1371/journal.pone.0067339.

Yoon SH, et al. (2005) Production of vanillin by metabolically engineered Escherichia coli. Biotechnology Letters 27:1829–1832. doi:10.1007/s10529-005-3897-2.

Zamzuri NA and Abd-Aziz S (2013) Biovanillin from agro wastes as an alternative food flavour. Journal of the Science of Food and Agriculture 93:429–438. doi:10.1002/jsfa.5962.

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