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Application of Plant Biotechnology in Sustainable Agriculture: Development of High-Value Phytochemicals for the Food and Cosmetics Industries

YU-TENG, LI (Ben)

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Corresponding Author:
ben780903@hotmail.com

Abstract

The rapid progress of plant biotechnology over the past decade is gradually reshaping the framework of sustainable agriculture. Through metabolic engineering, gene editing, plant cell and hairy root factories, elicitation strategies, and green extraction technologies, researchers can effectively enhance the yield and stability of high-value phytochemicals (such as polyphenols, flavonoids, carotenoids, terpenoids, resveratrol, etc.) (Martínez-Chávez et al., 2024; Van Beirs et al., 2025). These compounds have been widely applied in the food and cosmetics industries as natural colorants, antioxidants, anti-inflammatory agents, and UV protection ingredients, playing a significant role in promoting circular economy and sustainable resource utilization (Bekavac et al., 2025; Machado et al., 2024). Meanwhile, the integration of gene editing (particularly CRISPR/Cas technology) with synthetic biology enables researchers to redesign plant metabolic networks, directing carbon flux toward the biosynthesis of specific target metabolites (Chen et al., 2024; Zhang et al., 2024). Furthermore, the application of plant cell and hairy root cultures in bioreactors is becoming a stable and scalable production platform (Biswas et al., 2023; Häkkinen et al., 2024). Combined with green extraction methods (such as natural deep eutectic solvents, NADES) and nanoencapsulation technologies, the environmental friendliness and bioavailability of phytochemicals have been enhanced (Hikmawanti et al., 2021; Lei et al., 2024). In summary, plant biotechnology is not only a tool for improving agricultural productivity but also an important driving force for promoting value addition and sustainability in the food and cosmetics industries. However, future challenges regarding cost, regulation, safety, and scale-up production still need to be addressed.

INTRODUCTION

The core objective of sustainable agriculture is to achieve food security, environmental protection, and economic benefits simultaneously (Heuvelink et al., 2025). Against this backdrop, phytochemicals have become a focal point of research. These natural secondary metabolites—including flavonoids, phenolic acids, terpenes, carotenoids, and alkaloids—exhibit multiple bioactivities such as antioxidant, antimicrobial, anti-inflammatory, anticancer, and anti-UV effects (Elbouzidi et al., 2025; Păcularu-Burada et al., 2024). Consequently, they are not only key molecules for plant self-defense but are also widely used in the food and cosmetics industries as vital natural resources driving the health and beauty sectors.

However, the production of phytochemicals from conventional sources is often constrained by environmental conditions, cultivation limits, and inherently low natural yields. For example, the natural source of paclitaxel is extremely limited, necessitating artificial synthesis and scale-up via yew cell factories and hairy root cultures (Rezazadeh et al., 2024; Xie et al., 2025). Similarly, functional compounds such as resveratrol and anthocyanins occur at low levels under natural conditions, requiring metabolic engineering and controlled-environment agriculture to increase their abundance (Pramanik et al., 2024; Yuan et al., 2025). **Plant biotechnology** provides solutions to these challenges. Its core technologies include:

1. **Metabolic engineering and genome editing** — precisely regulating metabolic pathways to enhance the synthesis of specific compounds (Chen et al., 2024; Devi & Boro, 2023).
2. **Elicitation strategies** — using biotic or abiotic factors to trigger plant defense responses and increase secondary-metabolite yields (Selwal et al., 2025; Bajaj et al., 2025).
3. **Plant cell and hairy root factories** — stable production platforms under controlled conditions suitable for industrial scale-up (Biswas et al., 2023; Mirmazloum et al., 2024).
4. **Green extraction and delivery technologies** — environmentally friendly methods that improve recovery and stability of phytochemicals (Hikmawanti et al., 2021; Ferreira et al., 2024).

Following this framework, this paper systematically reviews the applications of plant biotechnology within sustainable agriculture, with a focus on developing high-value phytochemicals for the food and cosmetics industries.

RESEARCH METHODOLOGY

Applications of Plant Biotechnology in Sustainable Agriculture

The core challenge of sustainable agriculture lies in how to simultaneously increase crop yield and quality while reducing negative environmental impacts. Within this framework, plant biotechnology plays multiple roles across molecular to systemic levels—particularly in four key areas: enhancing crop stress tolerance, reducing chemical inputs, valorizing agricultural by-products, and advancing controlled environment agriculture (CEA).

Enhancing Crop Stress Tolerance

Climate change has intensified drought, salinity, and extreme weather events, posing severe risks to crop productivity. Gene editing and metabolic engineering provide precise regulatory tools to improve crop resilience and nutritional quality. For example, Chen et al. (2024) reported that modifying salt-tolerance genes in rice and wheat using CRISPR technology significantly increased survival and yield without compromising agronomic traits. Similarly, Prado et al. (2024) applied CRISPR in citrus and coffee to enhance disease resistance while simultaneously increasing polyphenol content. Moreover, synthetic biology and AI-assisted design are increasingly being used in crop improvement. Zhang et al. (2024) demonstrated that predictive AI modeling can optimize metabolic network regulation more efficiently, reducing trial-and-error costs and accelerating new cultivar development. These findings indicate that gene editing not only strengthens stress resistance but also enhances the accumulation of functional phytochemicals.

Reducing Dependence on Chemical Fertilizers and Pesticides

Another challenge in sustainable agriculture is the overuse of chemical inputs. Through elicitation and genetic modification, plant biotechnology can stimulate defense-related metabolic pathways, reducing the need for synthetic pesticides. Selwal et al. (2025) found that treating plant cells with biotic elicitors such as yeast extract and methyl jasmonate significantly increases the production of flavonoids and phenolic acids, thereby enhancing antimicrobial and disease resistance. Martínez-Chávez et al. (2024) further demonstrated that nanoparticles, as abiotic elicitors, act synergistically with metabolic engineering to substantially increase antioxidant yields in cell factories. These studies show that elicitation techniques can strengthen plant immunity and reduce environmental chemical burdens without additional pesticide use.

Valorization of Agricultural By-products

Agricultural and food-processing by-products are often regarded as waste, yet they contain abundant untapped phytochemicals. Recent studies emphasize green extraction and transformation technologies for high-value recovery. Bekavac et al. (2025) reported that fruit-processing by-products rich in polyphenols and antioxidants can be extracted using NADES and nanoencapsulation for use as functional food ingredients and natural preservatives. Rosales et al. (2023) found that grape skins and apple pomace contain high polyphenol levels; combining green extraction with enzymatic hydrolysis significantly enhances antioxidant activity and extends food shelf life. Rodrigues et al. (2025) highlighted that this valorization pathway aligns with the principles of a circular and zero-waste economy, simultaneously generating environmental and economic benefits.

Controlled Environment Agriculture (CEA) and Plant Factories

CEA technology integrates plant factories, precision nutrient management, and LED-based lighting control to enable year-round production of functional phytochemicals. Bhattarai et al. (2025) showed that adjusting light spectra and temperature in medicinal plant cultivation significantly increases the accumulation of flavonoids and alkaloids. Yuan et al. (2025) demonstrated that using AI and IoT technologies in plant factories to monitor environmental parameters can stabilize and enhance the yield of functional metabolites. This approach not only ensures consistency in yield and quality but also reduces land and water consumption.

RESULTS AND DISCUSSION

Development of High-Value Phytochemicals in the Food Industry

The demand for phytochemicals in the food industry primarily focuses on functional ingredients, natural colorants, antioxidants, and food preservation. Advances in plant biotechnology have made their supply more stable and environmentally friendly.

Functional Ingredients and Nutritional Fortification

Gene editing and metabolic engineering offer new pathways for developing functional foods. Stra et al. (2023) reported that by regulating genes in the carotenoid pathway, researchers successfully enhanced β-carotene and lycopene contents in tomatoes and maize. Wang et al.

(2025) further proposed that synthetic biology strategies can be used to develop crops enriched in vitamin B1 and other micronutrients, helping to combat global malnutrition. Additionally, the use of CEA and plant factories enables year-round production of functional crops. Zhang et al. (2024) suggested that integrating synthetic biology with AI can enable dynamic control of crop nutrient composition, further increasing the functional component content in foods.

Development of Natural Colorants

Natural pigments are essential additives in the food industry. Compounds such as anthocyanins, betalains, and carotenoids not only provide natural coloring but also possess antioxidant properties. Pramanik et al. (2024) used genetic engineering to develop “RUBY” plants that significantly accumulated betalains, making them potential sources of natural food colorants. Khan et al. (2025) emphasized that advances in the biotechnological production of betalains are expected to gradually replace synthetic dyes. Tanaka et al. (2025) demonstrated that metabolic engineering and gene editing can greatly enhance the yields of pigments such as astaxanthin and fucoxanthin in brown algae—pigments that have not only food applications but also market potential in nutraceuticals and functional beverages.

Natural Antioxidants and Health-promoting Compounds

Polyphenols, resveratrol, and quercetin are key antioxidants forming the foundation of functional foods. Mirmazloum et al. (2024) reported that hairy root cultures can stably produce high concentrations of polyphenols and flavonoids, suitable as antioxidant food ingredients. Ren et al. (2025) showed that resveratrol possesses anti-aging and cardioprotective potential, and that production in plant factories can enhance yield and consistency. Meanwhile, nanoencapsulation technology improves the bioavailability of these molecules. Lei et al. (2024) reported that microencapsulation of polyphenols and resveratrol enhances their stability and absorption in the digestive tract—a technique now widely applied in functional beverages and dietary supplements.

Food Preservation and By-product Utilization

Natural preservatives and antimicrobials represent another important demand in the food industry. Bekavac et al. (2025) showed that polyphenols extracted from fruit by-products can significantly extend the shelf life of juices and dairy products. Usman et al. (2025) also noted that phytochemicals recovered from plant food waste through green extraction can be used as natural antimicrobial and preservative agents, reducing the need for synthetic additives. Additionally, Carasek et al. (2024) demonstrated that using NADES as green solvents for extracting polyphenols from by-products not only improves recovery efficiency but also reduces solvent-related environmental impacts. Collectively, these studies highlight how plant biotechnology can both supply novel functional ingredients and promote sustainable food manufacturing through waste valorization.

Development of High-Value Phytochemicals in the Cosmetics Industry

Owing to their natural origin, safety, and multiple bioactivities, phytochemicals have become key raw materials in the cosmetics industry. Recent studies highlight the growing importance of plant-derived antioxidants, anti-inflammatory compounds, natural UV filters, and plant stem cell extracts, which are gradually forming a sustainable and scalable supply chain.

Antioxidant and Anti-inflammatory Compounds

Plant polyphenols and flavonoids exhibit strong antioxidant activity, neutralizing free radicals and delaying skin aging. Păcularu-Burada et al. (2024) reviewed the increasing application of flavonoids (such as quercetin and catechins) in anti-inflammatory and anti-aging skincare formulations. Ren et al. (2025) further reported that resveratrol can alleviate photoaging-related skin damage by modulating antioxidant enzyme expression. Hairy root and plant cell factories are widely used for producing these active ingredients. Mirmazloum et al. (2024) demonstrated that hairy root technology enables large-scale synthesis of flavonoids and phenolic acids with high batch-to-batch stability, making it suitable for industrial cosmetic applications.

Natural Sunscreens and UV-Absorbing Molecules

Flavonoids and polyphenols in plants can absorb ultraviolet radiation, serving as natural alternatives to synthetic sunscreens. Shabrina et al. (2025) found that plant extracts rich in flavonoids exhibit excellent photostability in sunscreen formulations and provide dual functionality—antioxidation and photoprotection. Milutinov et al. (2024) also reported that natural polyphenols and pigments have significant potential as skin-protective agents, offering substitutes for common inorganic UV filters such as zinc oxide and titanium dioxide. In addition, the application of synthetic biology has enabled stable production of natural UV-protective molecules in cell factories. Pigments such as fucoxanthin and astaxanthin, produced in algal systems (Tanaka et al., 2025), are now being commercialized for use in skincare and anti-photoaging products.

Plant Stem Cells and Cell Factories in Cosmetics

Plant stem cell extracts are widely utilized in anti-aging and skin-repair formulations because they contain diverse growth factors and signaling molecules. Gardiki et al. (2025) reported that extracts from apple and alpine plant stem cells can promote the proliferation of human skin stem cells, improving wrinkles and photoaging signs. At the same time, plant cell factories offer a sustainable source of bioactives while reducing overexploitation of natural resources. For example, yew cell factories have been successfully commercialized for paclitaxel production, and similar platforms may be extended to other cosmetic actives in the future (Coombe-Tennant et al., 2025).

Reuse of By-products and Waste

Phytochemicals derived from food and agricultural by-products are increasingly being applied in cosmetics. Machado et al. (2024) demonstrated that polyphenols extracted from grape pomace, coffee grounds, and olive by-products possess significant antioxidant and moisturizing properties, making them viable substitutes for petrochemical-derived ingredients. Couceiro et al. (2025) emphasized that such substitution strategies are not only environmentally friendly but also cost-effective and enhance a brand's sustainability image.

Discussion

Despite the remarkable potential of plant biotechnology in sustainable agriculture and related industries, several key challenges remain:

1. **Scale-up Challenges**
   Although plant cell factories can stably produce high-value compounds at the laboratory scale, industrial-scale production still faces bottlenecks such as nutrient supply, metabolic flux control, and cost-effectiveness (Titova et al., 2024; Titova et al., 2025).
2. **Cost and Market Competitiveness**
   The production of natural compounds remains expensive and lacks price competitiveness compared to synthetic alternatives. Future research should focus on process optimization and by-product utilization to reduce production costs (Bekavac et al., 2025).
3. **Regulatory and Safety Issues**
   Regulations on gene-edited crops, nanocarriers, and plant-derived cosmetic ingredients vary across countries, creating uncertainty in commercialization pathways (Prado et al., 2024; Couceiro et al., 2025).
4. **Consumer Acceptance**
   Although consumers show a strong preference for "natural" products, skepticism persists toward gene editing and nanotechnology. This underscores the need for better science communication and transparency between researchers, industry, and consumers.
5. **Need for Interdisciplinary Integration**
   Achieving industrial implementation requires integrating genetic engineering, synthetic biology, nanotechnology, green extraction, and data-driven optimization—demanding multidisciplinary collaboration and investment (Zhang et al., 2024; Yuan et al., 2025).

CONCLUSION

Plant biotechnology has become a key driver for sustainable agriculture and high-value industrial innovation. Through the integration of metabolic engineering/CRISPR, elicitation strategies, cell factories, and green extraction and carrier technologies, researchers can provide stable and eco-friendly sources of functional ingredients for the food and cosmetics sectors.
Future research directions may focus on:

1. Industrial scale-up and cost optimization — leveraging AI and digital-twin technologies to predict and streamline production processes.
2. Regulatory harmonization — promoting unified international safety standards to facilitate global trade.
3. Circular economy models — converting agricultural and food by-products into functional compounds to achieve zero-waste production.
4. Personalized applications — integrating big data and nutrigenomics to develop functional foods and personalized cosmetics tailored to individual needs.

In summary, plant biotechnology stands not only as a cornerstone of modern agriculture and biopharmaceuticals but also as the core driving force propelling the food and beauty industries toward high-value creation, sustainability, and personalization.

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