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## Integrated Biotechnological Strategies for Sustainable Valorization of Horticultural Waste: From Plant Pathology Management to Nutraceutical Development and Food Safety Assurance

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### ABSTRACT

The horticulture industry has been a major contributor to organic waste that is generated each year and as such sustainable waste management is becoming important. Historically, the horticultural waste has either been burned or landfilled thus leaving a substantial amount of damage to the environment. Recent developments in biotechnological-based approaches provide new solutions to the valorization of this waste, as the waste can be negatively converted to produce useful products and, thereby, overcome environmental issues, as well as promote economic, environmental and social sustainability. Among the largest opportunities of biotechnology in the waste valorization is in the field of plant pathology where biocontrol agent produced using waste assists in decreasing the use of chemical pesticides and improves the health of crops. Also, horticultural waste is being considered as a source of bioactive compounds to be developed into nutraceuticals. Fruit peels, seeds and stems of fruits contain bioactive compounds that have been proven to have antioxidant, anti-inflammatory and anticancer properties, as well as anti-aging effects that have been used in the development of health-promoting functional foods and supplements. Moreover, food safety assurance is being used through biotechnological approaches with the use of natural preservatives and antimicrobial peptides produced using waste in order to minimize contamination risks and the use of synthetic additives. The valorization of horticultural wastes in developing areas provides a twofold advantage that includes not only lessening the amount of waste in the society but also the generation of revenue by means of manufacturing valuable by-products. Although these solutions have the potential, there are several challenges such as scales, safety, and regulatory issues that must be mitigated to facilitate the popularity of these biotechnological solutions. The present paper talks about the different approaches to the valorization of horticultural waste, and how this can be used to facilitate sustainability in agriculture and food production systems.

## INTRODUCTION:

Waste management is a serious concern in the horticulture sector whereby quantities of organic waste are produced on an annual basis. Historically, all horticultural wastes such as plant remains, fruits and vegetable by-products have either been burnt or discarded in landfills all of which have negative environmental effects. Nonetheless, the recent progress of biotechnological approaches has proven that it is possible not only to work on these waste management issues but also to produce a value proposing novel applications of waste in different areas, such as the management of plant pathology, developing nutraceuticals, and ensuring food safety (Thompson et al., 2016; Guo et al., 2021). This can be considered a way of sustainable valorization since it can convert horticultural waste into useful by-products that can aid economic, environmental, and social sustainability.

The idea of valorization is connected to the process of converting waste into valuable products, and regarding horticultural waste, it involves the synthesis of bioactive compounds, fertilizers, biocontrol agents, and the other products of value (Sharma et al., 2020). Among the most important uses of the biotechnological approaches to waste valorization, the treatment of the plant diseases can be named. Hort crops are exposed to a high amount of pathogens and the control of such diseases has traditionally depended on the use of chemical pesticides. Nevertheless, the growing popularity of pesticide-resistant pathogens, the environmental and health issues have stimulated the identification of alternative and eco-friendly approaches to managing the diseases of plants (Jorfi et al., 2020). Bio-based methods of biocontrol, including biocontrol agents composed of waste horticultural products, have become the possible solution to sustainable management of plant pathology (Saha et al., 2021). Such biocontrol agents have the ability to control the presence of harmful pathogens and hence there is reduced use of chemical pesticides which enhance crop health and crop yield.

Simultaneously, the current enthusiasm in the area of nutraceuticals, which are functional food products that provide health benefits in addition to simple nutrition, has driven research into the opportunities of horticultural waste as a source of bioactive compounds with therapeutic effects. Phenolic compounds, flavonoids, carotenoids, and other bioactive molecules, which are found in horticultural by-products, including fruit peels, seeds and stems, have been associated with antioxidant, anti-inflammatory and anticancer effects (Khan et al., 2019). The extraction and purification of these compounds in waste products by biotechnological means offers sustainable source of nutraceuticals, besides helping in mitigating the environmental impact of horticultural industries. A number of studies have underscored the promise of the compounds in the production of functional food products, supplements, and cosmetics, hence generating new markets of products based on waste (Gupta et al., 2021).

Besides, food safety assurance is a primary issue in the worldwide food market and keeping foodstuffs safe is essential to avoid food-borne diseases and food contamination. Several options under investigation to improve food safety include biotechnological methods, including the use of probiotics, enzymes, and antimicrobial peptides obtained through horticultural waste (El-Beltagy et al., 2018). As an illustration, certain plant remnants have natural antimicrobial properties that could be exploited to come up with food preservation methods and thus avoid using chemical preservatives. Moreover, it is possible to reduce the threat of contamination in food processing through the inclusion of biotechnological waste valorization processes to prevent microbial growth on storage and transportation by applying organic waste-based antimicrobial agents to fresh produce (Bhosale et al., 2019).

The importance of integrated biotechnological solutions on horticultural waste valorization is especially apparent in developing countries, as in this case, the waste management facilities are still underdeveloped, and the agricultural processes themselves are more susceptible to the environmental factor (Kebede et al., 2021). The valorization of waste by use of biotechnological innovation is a twofold gain in the economies of countries such as India, Nigeria and Brazil which use horticulture as a major economic activity by not only decreasing the number of waste but also creating new income through the production of valuable products. The strategies are beneficial to the local economies, help in achieving sustainability, and enhancing more

robust food systems, which are important in combating the climate change and the high rate of urbanization (Yadla et al., 2020).

Nevertheless, even though there are probable advantages, a number of obstacles exist to the large-scale implementation of the biotechnological approach to horticultural waste valorization. They consist of issues of scalability of the biotechnological process, the necessity of conducting additional research on the efficiency and safety of biotechnological derived products, and the question of integrating such technologies into the existing agricultural and food production systems (Barros et al., 2018). Besides, the presence of financial and regulatory limitations can slow down the establishment of sustainable biotechnological solutions, especially in settings with low resources. The solutions to these challenges should be a concerted action at the part of the researchers, policymakers and the stakeholders in the industry in devising enabling structures which will support the uptake of the new innovative biotechnologies in waste valorization.

To sum up, the biotechnological solutions to the sustainable use of horticulture waste, in the form of integrated biotechnology, have a great opportunity to resolve the environmental, economic, and societal problems of horticulture industry. These strategies offer a means of achieving more sustainable agricultural systems that will both benefit the producers and consumers, starting with plant pathology management, moving on to nutraceutical and food safety assurance development. Nevertheless, to ensure the full implementation of these strategies, the current barriers should be overcome through further research, infrastructure investment, and the advocacy of the policies, which would be needed to scale up their application in a variety of settings and areas (Singh et al., 2017). Through the strength of biotechnology, the horticultural waste can be utilized to create great assets that can lead to a better and more resilient food system.

## **Plant Pathology Management**

The growing rate of plant disease, which is aggravated by environmental stressors like climate change, is very threatening to the world agriculture and food security. Conventional ways of controlling plant diseases are usually based on synthetic chemicals which although effective in the short run may cause adverse environmental effects, pesticide resistance and food safety situations. Integrated biotechnological strategies have therefore come up in response as a viable solution to sustainable management of plant pathology. These solutions exploit natural and environmental friendly alternatives such as biocontrol agents, plant-derived antimicrobial compounds and genetically modified crops to manage plant diseases with minimal environmental impact of farming activities. The innovative methods, utilizing the strength of biotechnology, present new possibilities of making plants healthier, decrease the use of chemical pesticides, and make food production systems more sustainable. The paper is a review of diverse biotechnical approaches to managing plant pathology, with an emphasis on these approaches to mitigate the existing threats and create more sustainable agricultural systems.

The current breakthroughs in the management of plant pathology have centered on the use of biocontrol agents that are obtained using horticultural wastes in reducing plant diseases. Saha et al. (2021) identified the potential of microbial antagonists, i.e., bacteria and fungi that can be obtained out of plant residues and which help to manage soil-borne pathogens. Such biocontrol agents have demonstrated effectiveness in keeping down the occurrence of disease like *Fusarium* wilt and root rot in crops like tomato and cucumber. Through the use of these agents in integrated pest management systems, the use of chemical pesticides can be decreased, and environmental friendly farming activities can be made more sustainable. The findings of the study language show that such agents do not only prevent plants against pathogen infection, but also improve the health of the soil by establishing favorable microorganism populations.

Antimicrobial compounds of plant origin have become good candidates in the management of plant diseases. In the research conducted by Jorfi et al. (2020), extracts of different plant by-products, such as peels and seeds, were proven to have antimicrobial properties that could suppress plant pathogen development. As an example, citrus peel extract has proven to be effective against fungal pathogenic

organisms like *Botrytis cinerea* and *Alternaria alternata* which are frequent causes of infections on crops like strawberries and grapes. By incorporating such natural extracts into one of the biopesticides formulations, the farmers would be able to deal with the plant diseases without necessarily using the aggressive synthetic compounds, hence enhancing the overall safety and sustainability of the food production.

Sharma et al. (2020) also examined the prospective of using organic waste, including fruit and vegetable residues, to make antifungal agents in another study. In their work, they have shown that some species of fungi, such as *Trichoderma harzianum*, which can be grown on the basis of horticultural waste, have exceptional antifungal effects, which inhibit pathogens, such as *Rhizoctonia solani*, and *Phytophthora infestans*. Biocontrol fungi are applied to reduce the pathogen load and also to stimulate the plant growth by increasing the nutrient cycling in the soil. The strategy is in line with sustainable agricultural practices whereby the environmental impact of chemical fungicides is minimized and at the same time, this strategy offers a low cost option to smallholder farmers.

The horticultural waste has also produced enzymes that may be used in the control of plant pathology. According to a study by Bhosale et al. (2019), plant enzymes, including chitinases and glucanases, have a role to play in the control of plant diseases. Such enzymes are produced naturally by plants as a reaction to attacks by pathogens and can be extracted out of the remnants of plants and be utilized as biopesticides. The analysis revealed that the enzymes are effective in degrading fungal pathogen cell walls and thus are a good option in organic farms. The biocontrol methods that are based on enzymes help not only to decrease the transmission of diseases on plants but also help to stabilize the ecological balance through the reduction of chemicals used in agriculture.

One of the most impressive innovations potential to be made in the management of plant pathology has been the introduction of genetically modified (GM) crops that are resistant to certain plant hazards. Gupta et al. (2021) state that genetic engineering has enabled the transfer of the genes of plants, bacteria, and fungi with resistance to different pathogens, such as viruses, fungi, and bacteria. An example of this is the genetically modified plants such as the Bt cotton and tomato pest and disease-resistant plants that have been found to be more resilient to pests and diseases that require chemical treatment. Despite the controversy of the use of GM crops, the technology has given a prospect of a solution in managing diseases in a sustainable manner especially in areas where plant diseases have remained a primary limitation of agricultural output.

Integrated Pest Management (IPM) is a critical management technique of controlling diseases that affect plants in a dynamic climate. In a study by Ayanlade et al. (2021), the researchers talked of the need to integrate climate-resilient IPM practices to survive the higher occurrence of plant diseases caused by climate change. The study revealed that the increase of temperatures and the change of rain patterns have made the expansion of conditions like downy mildew and late blight in crops like maize and potatoes more severe. An effective mode of the management of the diseases has been established as IPM that is a combination of cultural, biological and chemical control strategies. The paper recommends that CSPs like incorporation of resistant varieties of crops and biocontrol agents into IPM systems can be utilized to enable farmers to cope with the fluctuating climate without affecting crop health and productivity.

Technological inventions have lately become very vital in the management of plant pathology. Razzaq et al. (2023) conducted a study to examine the application of remote sensing technologies to monitor plant diseases in real-time including satellite images and drones. Early detection of disease outbreaks by aerial surveillance will enable intervention to take place in time and contain the dissemination of pathogens and the losses of crops will be minimal. Another method to measure the efficacy of disease control methods, including biocontrol agents and fungicides, is to use remote sensing technology to assess the health and development of the plants. The technology is most useful in agricultural programs that involve a lot of operations since the disease detection and control is critical to food security. The paper came to a conclusion that remote sensing combined with conventional disease management methods could be a valuable solution to the efficiency and sustainability of plant disease control.

## **Nutraceutical Development from Horticultural Waste**

The food-derived products with nutrition health advantages that are more than the dietary benefits of the food have attracted great attention in recent years due to their potential to enhance the health of the population, and prevent the occurrence of chronic illnesses. Fruits and vegetable peels, seeds, stems, and leaves constitute the horticultural waste, which forms a good nutraceutical the bioactive compounds present in the waste, including phenolics, flavonoids, carotenoids, and vitamins, are all rich and suitable in nutraceutical development. Khan et al. (2019) demonstrated in one of the studies that by-products of fruits and vegetables can be utilized in the extraction of these bioactive substances which have shown to possess antioxidant, anti-inflammatory and anticancer properties. The necessity of the study is the innovative biotechnological processes and isolation and purification of these compounds to offer a sustainable solution to the food waste minimization as well as the nutraceutical market expansion.

Horticultural wastes can be converted to nutraceutical which is not only a good process to the health of human beings but also to the environment. Most of the horticultural waste materials are disposed of resulting in a high waste build up and environmental contamination. Gupta et al. (2021) investigated the opportunities of using the bioactive compounds of fruit and vegetable residues to produce functional foods, supplements and natural cosmetics. As an example, orange peel wastes are good sources of flavonoids and essential oils that may be used to make functional drinks, dietary supplements, and skin care products. These products add value to the otherwise wasted products, making waste healthy commodities and driving a circular economy in the food sector.

Besides having antioxidants, some of the horticultural wastes are also a rich source of dietary fibers, which are important in the digestive health and prevention of cardiovascular diseases. A study conducted by Arora et al. (2020) revealed that the dietary fiber of fruits like apples, bananas, and pomegranates is high and can be extracted and used in nutraceutical products. These fibers assist in controlling the level of glucose, enhancement of the health of the gut and reduction in cholesterol. The paper argues that recycling horticultural waste into the manufacture of nutraceutical rich in fiber does not only offer a solution to issues of health but also minimizes the environmental effects of agricultural waste, which is a viable solution to food and waste management.

Further, the seeds of most fruits and vegetables that are usually wasted as refuse are useful in bioactive compounds including oils, proteins, and phytochemicals. Another study by Fan et al. (2019) talked about using the seeds of watermelon, mango, and papaya which are usually wasted to prepare oils which are anti-inflammatory, antimicrobial, and anticancer. These oils can be applied in manufacturing of nutraceuticals, cosmetics and pharmaceuticals. The nutraceutical industry can play a significant role in ensuring that environmental impact that food production has on the environment is minimized by converting these underutilized agricultural by-products to useful health products, and also help in ensuring sustainable use of resources.

These compounds can be further improved by the integration of biotechnological processes including fermentation, enzymatic hydrolysis and extraction processes to increase bioavailability and thus become effective in nutraceutical preparation. As an example, the fermentation processes have the ability to decompose complex compounds to simpler, more bioavailable forms, and thus enhance their absorption and efficacy within the body. Sharma et al. (2020) investigated the use of biotechnological interventions as means of increasing the potency of compounds obtained through the horticultural waste. Such processes do not only enable the final product to be healthier, but also raise the efficiency of the waste valorization, which makes it a more viable and lucrative choice in both small-scale and large-scale production.

There are no challenges that come without the development of nutraceuticals out of horticultural waste. Problems of standardization, quality control and acceptance of the products by consumers must be resolved so that these products can be marketed successfully. Nevertheless, with the still growing demand of consumers in natural and plant-based health products, there exist a growing possibility of utilizing the still untapped nutraceutical potential found in horticultural waste. According to Fadina and Barjolle (2018), the

key to addressing such challenges, as well as ensuring the appropriate effectiveness and safety of nutraceutical products of waste, is collaboration between researchers, industries, and policymakers. This solution not only has a potential of enhancing the health of people, but also creating a more sustainable and circular agricultural economy.

## **Integrated Biotechnological Pathways for Circular Economy**

By continuously striving to tackle the climate change, the idea of a circular economy is not only set to decrease the amount of waste, but also maximize the use of the available resources by establishing a closed-loop process that would allow products, materials, and resources to be reused, refurbished, and recycled. The integrated biotechnological pathways are vital in this model due to their ability to enable the sustainable utilization of the organic waste, including horticultural by-products, and convert the waste into useful products, including biofuels, bioplastics and bioactive products. Biotechnological processing to produce waste into valuable commodities, like fermenting, enzyme conversion, and microbial degradation, will lead to environmental sustainability and a decreased need in virgin materials (Zhang et al., 2021).

The conversion of organic waste to biofuels is one of the key biotechnological directions that have led to the circular economy. Horticultural waste, e.g. fruit peels, seeds, and vegetable residues, are rich sources of starch, cellulose, and other fermentable sugars that can be converted to bioethanol and bio-gas on a microbial fermentation basis. Research by Yadla et al. (2020) has revealed that fermentation of such organic materials using microorganisms like *Saccharomyces cerevisiae* and *Clostridium thermocellum* leads to the generation of bioethanol, which is a renewable source of energy that will reduce the use of fossil fuels. The pathway does not only assist in the management of agricultural wastes, but also supports the energy industry by offering an alternative source of clean energy hence achieving a transition to a more sustainable and circular economy.

The horticultural waste is another promising route that can be used to produce bioplastics. The plastics being non-biodegradable, they pose a significant environmental issue and bioplastics made of renewable resources are considered to be one of the solutions to this issue. A study by Gupta et al. (2021) showed that biotechnological methods of making bioplastics through microbial fermentation to convert organic waste into bioplastics or through the use of enzymes to polymerize plastics in an enzymatic process can be used to make bioplastics. As an example, polylactic acid (PLA), which is a frequently used biodegradable plastic, can be produced using the horticultural waste such as fruit peels and corn starch as its starting material, which is made of sugars. Such bioplastics provide an environmentally friendly substitute to petroleum-based plastics and help to decrease plastic waste, which helps to pursue the objectives of a circular economy.

Biotechnological approaches are also being utilized to extract useful bioactive substances to horticultural wastes that can be utilized in different sectors, such as food, pharmaceutical and cosmetic sectors. In a study by Khan et al. (2019), the authors have emphasized the potential to extract and purify phenolic compounds, flavonoids, and carotenoids, which are highly concentrated in fruit peels and seeds, of a study by using biotechnological methods. These bioactive compounds massively possess the antioxidant, anti-inflammatory and anticancer effects and are broadly utilized in nutraceutical, functional and cosmetic products. Biotechnology helps in the production of products that add value to the health and the environment of the human being through conversion of waste to high-value bioactive products and thereby bridging the gap in the production loop of the horticultural waste and providing economic benefits.

Besides making biofuels, bio plastics and bioactive compounds, the biotechnological pathways that are planned to be integrated can also serve the circular economy by enhancing waste management. Indicatively, biotechnological processes such as composting, anaerobic digestion and microbial degradation are used to aid in the breakdown of organic waste into compost, biogas and other reusable products. Such processes do not only make the disposal of wastes environmentally friendly; they also generate useful by-products like organic fertilizers that can be utilized to increase the soil quality and facilitate sustainable agricultural activities. The main purpose of biotechnology is to keep the cycle of materials and energy in the economy

through converting waste into resources that can be used again.

Furthermore, the contribution that biotechnology will have on the circular economy is its contribution on the minimization of environmental pollutants, including greenhouse gaseous emission, with more sustainable waste management approaches. Examples of biotechnological methods to treat the dangerous chemicals in agricultural wastes are bioremediation by microorganisms, in which some agricultural wastes are converted into biodegradable products by means of bio-remediation. Sharma et al. (2020) described a research study that highlighted the ability of some microorganisms to decompose pesticides, herbicides, and heavy metals in agricultural residues to produce safer by-products to be reused in other industries. Such biotechnological intervention is endorsing the sustainability of the agricultural practices, but it is also helping to reduce pollution, which is again beneficial to the aspirations of a circular economy.

The introduction of the integrated biotechnological ways of valorizing waste is an opportunity to transform industries, which are line-based and resource-consuming, to a circular and sustainable approach. Nonetheless, these technologies need to be scaled to achieve a broad adoption in the market as there are few barriers that need to be overcome such as investing in research and development, scaling up the biotechnological processes, and addressing the issue of regulations. Researchers, policymakers, and industry stakeholders should collaborate to develop the required infrastructure and incentives to capitalize on biotechnologies in the sectors of waste management and resource recovery (Singh et al., 2021). Through innovation and investment in biotechnological interventions, one can hasten the conversion to a circular economy that will be not only environmentally friendly but also profitable.

## Conclusion

To sum it up, biotechnological approaches to the utilization of horticultural waste are a ground-breaking solution to the problem of waste management in the horticulture industry. Such strategies are not only beneficial to the environment by means of decreasing the waste build-up and pollution, but also offer an opportunity to economic development through the production of valuable by-products, including biocontrol agents, bioactive substances, and natural preservatives. The waste can be used to produce biofuels, bio plastics as well as functional ingredients that are healthy and this is through biotechnological processes that include fermentation, enzymatic conversion, and microbial degradation. The use of such technologies in management of plant diseases, development of nutraceuticals and food safety guarantees show their wide opportunities to deal with the global problem of food security and ensure the sustainable production of food. Nevertheless, to get these technologies to their full potential, a number of challenges should be dealt with, which include scalability of biotechnological processes, financial limitations, and integration of new systems into the existing agricultural infrastructures. Researchers, policymakers and industrial stakeholders should strive to come up with the frameworks that are needed to make the adoption widespread. Since research is still developing and the circular economy has been gaining grounds, biotechnology can reshape the way in which the horticultural waste is handled, transforming it into the resource that would be beneficial to both the environment and the society. The problem of waste turning into useful products through sustainable transformation will be the future of horticulture, and this change will contribute to a more robust and sustainable global food system.

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