Building Sustainable Communities: Integrating Biotechnological Waste Valorisation and Spirulina-Based Biostimulants in Modern Agronomy

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Modern agriculture is confronted with a threefold challenge: escalating global food demand, environmental degradation driven by intensive farming practices and increasing climatic instability. Addressing these interconnected pressures requires a paradigm shift from linear, input-intensive agricultural systems toward circular, resource-efficient models. This article synthesizes recent advances in agro-industrial waste management through biotechnological valorisation and evaluates the emerging role of *Spirulina*-based biostimulants as a sustainable tool for crop intensification. By integrating waste-to-resource technologies with microalgal biostimulant production, agriculture can simultaneously reduce environmental burdens, improve soil and plant health and enhance productivity. Such integrated approaches form the foundation of resilient, community-centred agroecosystems aligned with the principles of the circular bioeconomy.

The Growing Crisis of Agricultural Waste

The global expansion of agriculture and horticulture has significantly increased the generation of agro-industrial waste. Current estimates indicate that agricultural systems worldwide produce nearly 23.7 million tonnes of biomass waste daily. Alarmingly, approximately 40–45% of total agricultural output is lost along the supply chain, encompassing pre-harvest losses due to pests and diseases, post-harvest handling inefficiencies, processing residues and retail- and consumer-level food waste. When improperly managed, agro-industrial residues pose serious environmental risks. Uncontrolled decomposition of organic waste releases methane, nitrous oxide and other greenhouse gases, contributing to climate change and atmospheric pollution. Traditional disposal practices, such as open dumping, field burning and landfilling, not only exacerbate these emissions but also represent a substantial loss of valuable bioresources rich in carbohydrates, proteins, lignin, polyphenols and micronutrients. In this context, agricultural waste should no longer be viewed as a liability but rather as a renewable feedstock capable of supporting sustainable production systems. Biotechnological interventions provide viable solutions to recover value from these residues while minimizing environmental impacts.

Biotechnological Tools for Agro-Waste Valorisation

Biotechnology offers transformative pathways for converting agro-industrial waste into high-value bioproducts, thereby closing material loops within agricultural systems. Through microbial, enzymatic and physicochemical processes, waste streams can be repurposed into bio-enzymes, organic acids, biopolymers, pigments and biofertilizer components.

a) Solid-State Fermentation (SSF)

Solid-state fermentation is widely recognized as an efficient and cost-effective method for valorising lignocellulosic agricultural residues such as straw, husks and bran. In SSF systems, microorganisms grow on moist solid substrates in the absence of free-flowing water. Fungal species such as *Aspergillus niger*, *Trichoderma reesei* and bacterial strains including *Bacillus* spp. are commonly employed to produce industrially relevant enzymes, including cellulases, xylanases and proteases. Beyond enzyme production, SSF enhances substrate digestibility and nutrient availability, making the fermented residues suitable for use as organic soil amendments or biofertilizer components.

b) Valorisation of Fruit and Vegetable Residues

Processing wastes from fruits and vegetables—such as apple pomace, mango peels, citrus rinds and grape marc is particularly rich in bioactive compounds, including polyphenols, flavonoids, carotenoids and dietary fibers. Advanced extraction technologies, such as supercritical CO_2 extraction, ultrasound-assisted extraction and enzyme-assisted methods, are increasingly used to recover these compounds efficiently and sustainably. Recovered bioactives find applications in agriculture as natural antioxidants, plant growth enhancers and stress-mitigating agents, reinforcing the link between waste valorisation and sustainable crop management.

c) Management of Potato Processing Effluents

Potato processing industries generate effluents characterized by high Chemical Oxygen Demand (COD) and Biological Oxygen Demand (BOD), posing significant wastewater management challenges. Biotechnological treatment using thermophilic bacteria or yeast strains such as *Saccharomyces cerevisiae* enables the conversion of these effluents into microbial biomass and value-added byproducts. The resulting biomass can serve as a protein-rich supplement or as a raw material for agricultural bioproducts, simultaneously addressing pollution and resource recovery.

Spirulina spp.: A Cornerstone of Sustainable Biostimulants

Among microalgae and cyanobacteria, *Spirulina* spp. (*Arthrospira* spp.) has emerged as a highly promising resource for sustainable agriculture. This filamentous, photosynthetic cyanobacterium is characterized by rapid growth, high biomass productivity and exceptional biochemical richness.

Biochemical Composition and Agronomic Potential

The biostimulant potential of *Spirulina* is rooted in its complex molecular composition:

- Proteins and Amino Acids: Accounting for approximately 60–70% of its dry weight, *Spirulina* biomass provides essential amino acids that serve as precursors for plant nitrogen metabolism and protein synthesis.
- Phytohormones: *Spirulina* contains naturally occurring plant growth regulators, including auxins (notably indole-3-acetic acid), cytokinins, gibberellins and jasmonic acid, which collectively influence cell division, elongation and stress signalling.
- Polysaccharides and Vitamins: These compounds act as signalling molecules, antioxidants and Osmo protectants, enhancing plant defence responses and metabolic efficiency.

Such a diverse biochemical profile makes *Spirulina* an ideal candidate for formulating next-generation biostimulants.

Physiological Effects of *Spirulina*-Based Biostimulants on Crops

The application of *Spirulina*-based biostimulants (SBBs) induces a cascade of positive physiological responses in plants across different growth stages.

a) Enhanced Germination and Seedling Vigor

Seed priming with aqueous or hydrolyzed *Spirulina* extracts, typically at concentrations ranging from 0.8% to 3%, has been shown to accelerate germination, improve seedling emergence and increase early biomass accumulation. These effects are attributed to enhanced enzymatic activity and improved hormonal balance during early development.

b) Improved Photosynthetic Efficiency

Foliar application of SBBs increases chlorophyll content, stomatal conductance and membrane stability. Studies on crops such as *Lactuca sativa* (lettuce) and *Eruca sativa* (rocket) demonstrate significant improvements in photosynthetic rate and overall plant vigor following SBB treatment.

c) Increased Nutrient Use Efficiency: *Spirulina*-based formulations enhance the bioavailability and uptake of essential nutrients, including nitrogen, phosphorus, potassium, calcium and magnesium. Improved root architecture and rhizosphere activity contribute to more efficient nutrient acquisition and reduced reliance on synthetic fertilizers.

d) Enhanced Tolerance to Abiotic Stress

The presence of antioxidants, polysaccharides and compatible solutes in *Spirulina* extracts strengthens plant tolerance to abiotic stresses such as salinity, drought and temperature extremes. These compounds mitigate oxidative stress and stabilize cellular structures under adverse conditions.

Economic Viability and the Circular Bioeconomy

Despite their proven agronomic benefits, the widespread adoption of *Spirulina*-based biostimulants is currently constrained by relatively high production costs compared to conventional agrochemicals. To overcome this barrier, an integrated biorefinery approach is essential. Coupling *Spirulina* cultivation with wastewater treatment systems can significantly reduce nutrient input costs while delivering environmental services through nutrient removal and water purification. Furthermore, a cascade utilization model allows for the sequential extraction of high-value products, such as phycocyanin and antioxidants, before the residual biomass is formulated into biostimulants. This approach maximizes resource efficiency and improves economic feasibility.

Conclusion

The integration of biotechnological agro-waste valorisation with microalgal biostimulant production represents a compelling pathway toward sustainable, climate-resilient agriculture. By transitioning from a linear "produce–use–discard" model to a circular bioeconomy framework, agricultural systems can reduce environmental footprints, enhance soil and crop health and meet the productivity demands of a growing global population. Such integrated strategies not only promote sustainable agronomy but also strengthen rural livelihoods and community resilience, laying the foundation for truly sustainable agricultural development in the 21st century.

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