UNIVERSITI TEKNOLOGI MARA

BULETIN APB

EDISI 16

Jun 2026

AKADEMI PENGAJIAN BAHASA
UNIVERSITI TEKNOLOGI MARA
CAWANGAN NEGERI SEMBILAN
KAMPUS SEREMBAN

BULETIN APB EDISI 16/2026
e-ISSN : 2682-7948

Agro-industrial Waste Valorisation

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Agriculture and food processing industries globally generate 1.3 billion tonnes of waste annually, accounting for about one-third of total global food production (Prado-Acebo et al., 2024; Rojas et al., 2022). Traditionally, this immense volume of waste, ranging from agricultural waste such as stalks and leaves to food industry waste such as peels, pomace, and spent grounds, has been disposed of through incineration or landfilling (Prado-Acebo et al., 2024). This linear "take-make-dispose" model poses severe environmental threats, contributing to greenhouse gas emissions and atmospheric pollution and wasting massive economic potential (Prado-Acebo et al., 2024; Sarangi et al., 2022).

However, this paradigm is shifting toward agro-based waste valorisation, a transformative strategy that converts organic residues into high-value products, fuels, and chemicals (Sarangi et al., 2022; Prado-Acebo et al., 2024). This practice goes far beyond mere waste management; it is a fundamental driver reshaping the food industry, fortifying global food security, and establishing a sustainability-focused circular bioeconomy (Rojas et al., 2022; Sarangi et al., 2022).

The impact of waste valorisation on the food industry is incredibly profound, shifting operations from high-disposal-cost centers to highly profitable, sustainability-driven closed-loop systems (Rojas et al., 2022). Industrial food processing generates significant concentrated waste streams, such as spent coffee grounds, olive pomace, and grape stalks, which retain high concentrations of valuable biomolecules (Prado-Acebo et al., 2024). Through targeted extraction techniques like pressurised liquid extraction or enzymatic hydrolysis, the food industry can recover highly sought-after bioactive compounds, including antioxidants, phenolics, functional proteins, and pectin (Rojas et al., 2022).

For instance, grape seeds and skins left over from winemaking are processed to extract anthocyanins and tannins, which are then reintegrated into the market as functional food ingredients, nutraceuticals, and natural cosmetics (Rojas et al., 2022; Prado-Acebo et al., 2024). Similarly, cocoa pod husks and coffee peels are transformed into dietary fibres and sugars for the food industry (Rojas et al., 2022).

Furthermore, agri-food waste serves as an excellent, cost-effective substrate for microbial bioconversion to produce crucial industrial enzymes. Fungal and bacterial cultures grown on residues such as coffee peel or wheat bran can secrete pectinases, proteases, and lipases, which are subsequently reutilised in the food industry to further process materials and enhance product quality (Rojas et al., 2022). By capturing these high-value components before utilising the remaining biomass for bioenergy, the food industry maximises its biovalue, eliminates waste management costs, and generates entirely new revenue streams (Prado-Acebo et al., 2024; Rojas et al., 2022).

Equally significant is the role of agro-waste valorisation in addressing critical challenges in global food security, serving as a crucial component of global sustainability efforts (Prado-Acebo et al., 2024).

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A prominent concern in the modern bioeconomy is the "food-fuel conflict," in which arable land and edible crops (such as corn or sugarcane) are diverted from food markets to produce biofuels, threatening food availability and driving up prices (Prado-Acebo et al., 2024).

By establishing second-generation biorefineries that rely exclusively on agricultural residues and non-edible byproducts, the energy sector can produce vital biofuels without competing for the fertile land needed to feed a growing population (Prado-Acebo et al., 2024; Sarangi et al., 2022). Beyond mitigating this conflict, valorisation directly contributes to agricultural productivity (Prado-Acebo et al., 2024). The solid organic residues that remain after the extraction of carbohydrates or biofuel fermentation can be transformed into nutrient-enriched bio-fertilisers and biomanure (Prado-Acebo et al., 2024; Sarangi et al., 2022). Applying these organic bio-fertilisers back to croplands enhances soil fertility, promotes healthy plant growth, and increases agricultural yields without the toxic runoff associated with synthetic chemical fertilisers (Prado-Acebo et al., 2024).

Additionally, some extraction processes focus on recovering low-molecular-weight peptides from by-products such as bovine bones, thereby introducing novel, sustainable protein sources into the animal feed and human nutrition supply chains (Rojas et al., 2022). By improving soil health and optimising nutrient extraction, the valorisation loop provides a robust defense against food scarcity and directly supports the United Nations' Zero Hunger sustainability objective (Prado-Acebo et al., 2024). Ultimately, these advancements lead to the transition toward a circular bioeconomy, which serves as the key framework for long-term sustainability (Prado-Acebo et al., 2024; Sarangi et al., 2022). This framework replaces the traditional "take-make-dispose" concept with the "5R" principles: reduce, reuse, recycle, recover, and restore (Rojas et al., 2022).

Instead of viewing biomass as refuse, advanced multi-product biorefineries utilise it as a versatile feedstock, fractionating its primary lignocellulosic components such as cellulose, hemicellulose, and lignin to extract maximum value in a zero-waste approach (Prado-Acebo et al., 2024). Industrial symbiosis is a critical enabler in this ecosystem, allowing traditionally separate industries to form collaborative networks in which the waste or by-products of one facility become essential raw materials for another (Salomone et al., 2020). For example, residues from food processing can be diverted to produce bioethanol, biomaterials, or even bio-based building products, thereby decoupling economic growth from the extraction of virgin fossil resources and severely limiting environmental degradation (Salomone et al., 2020; Sarangi et al., 2022). By integrating thermal, chemical, and biological conversion technologies, these systems transform an environmental liability into a localised engine for sustainable economic development (Prado-Acebo et al., 2024; Sarangi et al., 2022). Collaborative mechanisms, such as establishing ecologically equipped industrial areas or utilising shared infrastructure, ensure that the geographic proximity of these industries maximises resource efficiency (Salomone et al., 2020).

In conclusion, the integral multi-valorisation of agro-industrial wastes is a basis for modern sustainability and development (Prado-Acebo et al., 2024). The remarkable capability to transform crop stalks, fruit peels, and processing effluents into bio-based chemicals, functional ingredients, and organic fertilisers proves that agricultural waste is simply a misplaced resource (Sarangi et al., 2022; Rojas et al., 2022). To fully unleash the potential of these innovations, the food industry must adopt targeted extraction to maximise profitability, champion food security through non-competing biofuels and bio-fertilisers, and forge a circular bioeconomy through deep industrial symbiosis and integrated multi-product biorefineries (Prado-Acebo et al., 2024; Salomone et al., 2020). As these sectors aggressively adopt these closed-loop pathways, they will drastically reduce their environmental footprint, pioneer resilient economic opportunities, and safeguard the planet for generations to come (Prado-Acebo et al., 2024; Rojas et al., 2022).

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