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## BRIDGING THE GAP: FROM RESEARCH TO APPLICATION IN RESIDUAL PLANT BIOMASS VALORIZATION

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### **Introduction**

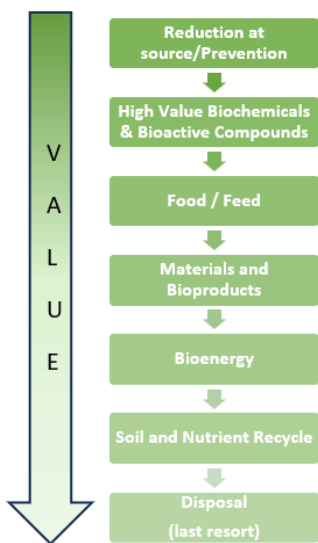
Residual plant biomass represents one of the most abundant yet underutilized renewable resources. Despite notable progress in biomass conversion and valorization, a substantial gap remains between laboratory innovation and industrial deployment. This communication aims to highlight recent advances in biomass valorization techniques that show promise for real-world application, with a focus on achieving zero-waste systems through comprehensive utilization of all biomass components.

Recent studies have demonstrated significant advances in eco-friendly, zero-waste techniques, but implementation remains limited. The challenge lies in developing economically feasible processes that can extract maximum value from all plant biomass components.

### **Hierarchical approach to biomass valorization**

A hierarchical framework for plant biomass waste valorization is presented, that prioritizes extraction of high-value components before conversion to energy or bulk materials. This approach aligns with circular economy principles and maximizes economic returns from biomass resources. The hierarchy typically follows high-value bioactive compounds extraction (pigments, antioxidants, pharmaceuticals, etc.), functional material isolation (fibers, proteins, specialized lipids), platform chemical production (building blocks for further synthesis), biofuel and energy generation (from remaining fractions), soil amendment, and carbon sequestration (from process residues).

Integrating *smart agri-food* value chains with *circular, zero-waste design and IoT/AIoT logistics* enables efficient residual plant biomass valorization, such as controlled-atmosphere storage of fresh fruits and vegetables to slow oxidative and enzymatic reactions, preserving chemical quality, minimizing losses, and enhancing sustainability.



**Figure 1.** Hierarchical approach to biomass valorization

Advanced extraction techniques for *selective molecules recovery*, eco-friendly techniques, and click chemistry have been reported to efficiently obtain *polyphenols*, *proteins*, and other *functional biomolecules* from biomass. Examples include pulsed electric fields, ultrasound or microwave-assisted methods, supercritical fluid, and enzyme-based extraction techniques. Antioxidants obtained through green chemical processes, polyphenols, flavonoids, carotenoids, along with proteins to enrich animal feed, natural pigments or hydrocolloid thickeners as functional food additives are examples of added value applications.

*Fiber valorization.* Lignocellulosic components of biomass can be transformed into valuable materials through: nanocellulose production for advanced materials, lignin depolymerization for aromatic compounds, hemicellulose conversion to xylitol and other sweeteners, cellulose functionalization for special uses, etc.

*Mineral recovery and utilization* - biomass ashes contain valuable minerals that can be recovered by selective leaching processes, membrane filtration technologies, precipitation and crystallization, electrochemical recovery systems.

*Nanomaterials from biomass* - emerging techniques for nanomaterial production from biomass include bottom-up synthesis using biomass-derived precursors, hybrid approaches combining biological and chemical processes, template-directed synthesis using biomass structures.

### **Conclusions and future directions**

Despite *significant advances*, several *challenges remain* for biomass valorization: process integration and scale-up difficulties, economic viability at commercial scale, feedstock variability, and standardization. *Future research* should focus on developing robust processes tolerant to feedstock variability, reducing energy and resource inputs for conversion processes, improving catalyst efficiency and recyclability, creating modular systems adaptable to different scales and contexts. The transition to zero-waste biomass utilization requires a paradigm shift from single-product focus to *comprehensive valorization strategies*.

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