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Waste alchemy in the age of industry 5.0: rethinking sustainable electronics

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Introduction

Industry 5.0 marks a new era of industrial innovation, combining automation and artificial intelligence with sustainability and human-centered approaches. Unlike previous industrial revolutions, it emphasizes environmental responsibility and circular economy principles.[1,2] This transition is essential for tackling global challenges such as climate change, biodiversity loss, and resource scarcity while aligning with the United Nations Sustainable Development Goals (SDGs), particularly SDG 9 (Industry, Innovation, and Infrastructure), SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action).

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One of the biggest hurdles in this shift is the vast amount of waste generated by the agricultural and food industries. A significant portion of this waste contains valuable natural organic materials (NOMs) that could be repurposed for sustainable electronics but remain largely untapped. Advances in (green) chemistry, materials science, and engineering offer an opportunity to transform these NOMs into functional electronic components, reducing reliance on virgin raw materials and minimizing environmental impact.

The problem: agricultural and food industry waste

Agriculture and food production generate massive amounts of waste every year. In Brazil alone, food loss is estimated to range between 23 and 82.1 million tons annually, according to the 2024 United Nations Environment Programme's Food Waste Index Report. Beyond wasted food itself, this represents a major inefficiency in the use of natural resources, like land, water, and energy.

Globally, food loss accounts for 14–17% of all food production and nearly 38% of total energy wasted in food supply chains.[3] Additionally, the food sector is responsible for about 30% of global energy consumption,[3] much of it from fossil fuels, increasing its carbon footprint. These inefficiencies contribute to approximately 26% of all human-driven greenhouse gas emissions, with a large share stemming from food that is never consumed.[3]

Beyond food waste, Brazil's agricultural sector produces vast biomass residues from crops such as sugarcane, corn, soybeans, rice, wheat, and coffee, along with fruits like bananas, coconuts, and oranges.[4] While some of these residues are

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Fig. 1 Key interconnected elements for the transition to sustainable electronic materials from agri-food waste, where chemistry enables the transformation of natural resources into functional materials for Industry 5.0.

repurposed for energy generation, soil conditioning, and animal feed, over 200 million tons remain unused or are burned, releasing pollutants into the atmosphere.[4]

Reimagining agricultural and food waste (AFW) as a resource instead of a burden is a crucial step toward sustainability. The circular economy model offers a promising alternative, shifting the perception of AFW from waste to valuable raw material.[5–7] Many discarded AFWs contain natural polymers, pigments, and carbon-based structures that can be refined for emerging electronic technologies. Targeted chemical processes can transform these materials into functional electronic components, reducing environmental impact while driving innovation.

Despite its potential, scaling up AFW valorization faces challenges related to economic feasibility, industrial adoption, and scalability.[7,8] Addressing these obstacles requires investment in advanced processing techniques, sustainable energy solutions, and supportive regulations (Fig. 1).[7] Aligning these efforts with frameworks like the European Green Deal and national bioeconomy policies can accelerate the transition toward a more sustainable technological landscape.

Opportunity: chemistry as a toolkit for sourcing and optimization

While NOMs offer promising solutions for sustainable electronics, their natural variability presents challenges for standardization and reproducibility.[7,9–11] Factors like species differences, environmental conditions, and extraction methods influence their properties, requiring precise processing to ensure consistency.[7,12]

Chemical sciences provide essential tools to address these challenges, offering efficient methods for the extraction, modification, and functionalization of NOMs. Traditional solvent-based extraction techniques remain widely used, but greener alternatives, such as deep eutectic solvents, supercritical fluids, and enzymatic processes, are gaining attention.[7,8,13] Advanced ultrasound and microwave-assisted extraction further enhance efficiency while reducing environmental impact.[7,8,13]

Beyond extraction, chemistry plays a vital role in transforming bio-based materials. Innovations in biopolymer-based conductors, bio-inspired nanocomposites, and naturally derived semiconductors are expanding the possibilities for sustainable electronics.[11,14,15]

A particularly promising approach is converting AFW into biochar, a carbon-rich material with high electrical conductivity and biodegradability.[16,17] Controlled pyrolysis can fine-tune its structure and composition, optimizing electronic properties and ion transport.[7] Heteroatoms functionalization with elements like nitrogen, sulfur, or phosphorus further enhances conductivity and electrochemical stability.[16,17]

Applications: adaptability of NOMs in emerging technologies

NOMs are attracting growing attention due to their biocompatibility, biodegradability, and functional versatility.[9,10] In green electronics, they are being explored for use in energy storage devices, sensors, electrochromic systems, and even light-emitting diodes.[11] An emerging and innovative application is edible electronic devices, which could revolutionize healthcare by enabling diagnostic and therapeutic tools that interact with the digestive system.[14] These technologies could also serve as smart markers in the food industry, monitoring product conditions during transportation.[14]

In neuromorphic electronics, NOMs are being integrated into memristors and electrolyte-gated transistors, mimicking synaptic behavior for energy-efficient, flexible, and biocompatible computing devices.[18] This paves the way for intelligent autonomous biosensors and human–machine interfaces.[18]

Biohybrid photovoltaics represent another exciting frontier. Natural dyes derived from NOMs enhance solar energy conversion in organic solar cells, improving light-harvesting efficiency.[19] Additionally, integrating biological components like photosynthetic proteins into solar cells mimics natural photosynthesis, offering a sustainable approach to renewable energy production.[19]

Ethics, social impact, and economic implications

Sustainable electronics go beyond environmental benefits; they also raise important ethical, social, and economic considerations.[5–7]

Ensuring global access to biodegradable materials, bio-based electronic components, and energy-efficient devices is essential for a just transition. Many regions rich in biodiversity and agricultural resources lack the infrastructure to turn these materials into high-value applications. Encouraging technology transfer, fostering international partnerships, and providing financial incentives can help bridge this gap, enabling more regions to benefit from circular economy solutions.[7]

Using AFW in electronics also has economic potential. Waste valorization can lower production costs and stimulate industry growth. Adopting bio-based polymers and biodegradable materials can replace petroleum-based components, reduce environmental impact, and create job opportunities in bio-based industries.[7] This shift particularly benefits rural economies by providing farmers with additional income streams and reducing regional economic disparities.

Sustainable electronics also contribute to reducing the environmental burden of technology. Current electronics manufacturing depends heavily on non-renewable resources, generating pollution and hazardous waste.[6] Incorporating AFW into the supply chain helps companies comply with tightening global e-waste regulations while reinforcing corporate responsibility. As sustainability becomes a key market driver, businesses embracing these innovations will gain a competitive edge.

Beyond industry benefits, repurposing AFW fosters eco-conscious consumer behavior. Public awareness of sustainability is growing, with increasing demand for recycled and biodegradable materials.[7,20] This shift can turn agricultural by-products into sought-after resources, driving ethical consumption. Engaging local communities in waste collection and processing can create jobs, particularly for marginalized groups, while improving resource efficiency and social cohesion.

The future: industry 5.0 and technological evolution

The use of waste-derived materials in electronics aligns perfectly with Industry 5.0's vision of sustainable innovation. Unlike the automation-driven focus of Industry 4.0, Industry 5.0 prioritizes collaboration between human intelligence and advanced technology, enabling smarter manufacturing that optimizes resources and minimizes waste.

The transition to sustainable electronic materials will depend on continued scientific breakthroughs, supportive policies, and industry commitment. Emerging initiatives are already pushing eco-friendly electronics forward, and policies focused on the bioeconomy and circular economy will be key drivers. Additionally, blockchain technology[1] can enhance supply chain transparency, ensuring the traceability and sustainability of bio-based electronic materials.

Conclusion

Valorizing AFW through chemical sciences is a crucial step toward sustainable technological progress. By improving resource efficiency and reducing waste, this approach advances environmentally responsible electronics. Leveraging green chemistry, advanced material processing, and bio-based alternatives, agricultural waste can be transformed into high-value components while minimizing environmental impact.

Industry 5.0 is more than just advancing technology; it's about redefining how industries interact with nature and society. By integrating AFW, NOMs, AI, and sustainable chemistry, this new era can create a more resilient economy and a healthier planet.

Conflicts of interest

There are no conflicts to declare.

Data availability

No primary research results, software or code have been included and no new data were generated or analyzed as part of this essay.

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