Multidimensional sustainability assessment of circular management of orange peel waste

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Adopting a circular economy approach helps significantly reduce waste levels and aligns with the EU's strategic objectives of prevention, reuse, and recycling. This approach maximizes resource efficiency by promoting the continuous circulation of materials, reducing the need for virgin inputs. Producers, processors, distributors, and end users are all connected by intricate networks of interactions and activities known as agri-food chains (Falcone et al., 2024). Italy, the EU's second-largest agricultural producer (ISTAT, 2023),confronts issues such as food waste and the effects of climate change. During the orange juice production process, approximately 55 million tons of orange peel waste (OPW), which is a mixture of pulp, seeds, and peel, is generated annually (Teigiserova et al., 2022), representing up to 60% of the fresh citrus weight.

In alignment with the European Green Deal (European Commission, 2019), the National Research Centre for Agricultural Technologies (AGRITECH, agritechcenter.it), proposes a comprehensive, large-scale, multidisciplinary research initiative as part of the Next Generation EU recovery plan. AGRITECH's goal is to tackle the diverse challenges of sustainable agriculture in Italy using an integrated approach to improve the competitiveness and sustainability of the Italian agri-food sector. This research is part of Spoke 8, focused on "New Models of Circular Economy in Agriculture through Waste Valorization and Recycling." In this area, partners are exploring the transformation of organic waste into high-value products, advancing sustainable agro-energy production through waste valorization, and developing biofertilizers.

This contribution presents two steps of a multi-dimensional sustainability assessment framework, including the following methods: (i) Holistic Diagnosis (HD) and (ii) Multi-Criteria Decision Analysis (MCDA) and Circular Economy (CE) Assessment. The focus is on evaluating a technology currently developed by a company to produce an orange-based biocomposite with a biopolymer matrix.

Through the HD, the research proposed an integrated evaluation approach providing a multidimensional understanding of the technology under investigation. This method facilitates informed decision-making when adopting scalable circular solutions. It is valued for enhancing understanding of complex systems and providing valuable insights into challenges and opportunities. To complement HD (Battistoni et al., 2019), the research applies the Systemic Design methodology, which allows for a more in-depth analysis necessary to identify sustainable pathways for development. While HD is not designed to evaluate in the traditional sense, it is suited to assess the overall health or 'well-being' of a product, process, or territory. The method involves examining the productive context of a company and the territory of provenience of the by-product OPW, mapping the flows of materials, energy, and information while considering the interrelationships among various actors and territorial characteristics. The result is a detailed map of complexity, which is the basis for the subsequent phases of the research, highlighting key relationships and areas of influence. Integrating HD with broader sustainability assessment frameworks ensures that the proposed solutions are both technologically feasible and sustainable from social, economic, and environmental perspectives. Then, an MCDA approach is proposed to frame the CE Assessment of the case study in comparison with further alternative technologies for OPW management.

Common uses for OPW include recycling it into animal feed, processing it using biological or thermochemical methods, and using it as a source for extracting active chemicals. Anaerobic digestion proves particularly effective in valorizing OPW: the biogas produced meets the plant's energy needs, while the resulting digestate is used as fertilizer for orange crops. This integrated approach ultimately reduces the Global Warming Potential impact (Ortiz et al., 2020). When thinking about turning OPW into animal feed, it can be easily dried and then pelletized to create the finished product. In addition, when OPW undergoes pyrolysis the resulting products (bio-oil, biochar, and other condensables) can be valorized in various ways, such as for biodiesel production, power generation, soil enhancement, and carbon sequestration. Using derived biochar as biofuel reduces the impact of global warming potential by up to 79% (Martinez-Hernandez et al., 2019). OPW is also utilized in the fabrication of materials for various applications; for instance, it is utilized in the creation of a biodegradable biocomposite material that is used creating design objects (Ortega-Gras et al., 2021). Other companies propose an alternative to animal-derived

leather, producing an eco-leather from the OPW combined with biopolymers (Pieroni et al., 2022); or cellulose fiber obtained from OPW to produce textiles used in the high fashion industry (D'Itria & Colombi, 2022).
The various possible uses of OPW imply the need to question, from a CE perspective, how the performance of alternative technologies can be measured through a multi-dimensional approach, including environmental, economic, and social dimensions. Starting from a literature review on MCDA applications in agricultural waste management (Lombardi & Todella, 2023), first of all, the relevant Key Performance Indicators (KPIs) that emerged in the selected literature review were considered (e.g., Koskiaho et al., 2020; Teigiserova et al., 2022; Illankoon et al., 2023). Second, enlarging the analysis to CE indicators in both scientific literature (e.g., Poponi et al., 2024) and regulations and standards (e.g., ISO 59020: 2024), a total of 21 circularity KPIs were developed and submitted to various OPW companies in Italy, as experts, to determine the significance of each indicator in their technology and the availability of data pertaining to each. Third, 14 circularity KPIs were selected based on the survey, and analyzed for various technologies, as a basis to frame their CE Assessment in a comparative perspective.

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