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Design and Interdisciplinarity for Sustainable and Innovative Valorisation of Agroindustrial Waste and Residues

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ABSTRACT

The paper aims to deepen the debate regarding the design discipline in relation to science, especially focusing on the possible outcomes generated by a concerted action between design and science in addressing the urgent environmental issues. In the research context, interdisciplinarity encourages new results and synergies through the exchange of knowledge and the construction of new paths. Although design is intrinsically interdisciplinary, nowadays the figure of the designer is changing, with designers markedly approaching and operating at the intersection of other disciplines, researching, and even experimenting on matter first hand in their works. However, although there is a lot of data and insights on collaborative research programs, there is a lack of empirical evidence on how to best implement interdisciplinarity, on the added value it produces and on how to overcome narrow disciplinary restrictions. The topic of the sustainable valorisation of agro-industrial waste and by-products is presented as a case study of virtuous collaboration between design and science. The agro-industrial sector represents a driving force in the global economy however, it is accompanied by remarkable amounts of residues and waste generated by agronomic practices and industrial manufacturing which, according to sustainability and circularity principles, can be transformed into valuable resources through systemic approaches. In particular, the opportunities generated by the collaboration between chemists and designers for the extraction of bioactive compounds from biomasses of the wine and edible flowers production chain are discussed, through the adoption of sustainability and circularity principles through the entire process.

Keywords: Design and science, Interdisciplinarity, Agro-industrial waste valorization, Circular design, Circular economy, Design for sustainability

INTERDISCIPLINARY PRACTICES TO FOSTER THE INTERACTION BETWEEN DESIGN AND SCIENCE

The collaboration between design and science to address environmental urgencies is a promising approach that can lead to innovative and sustainable solutions. Designers bring a unique perspective to the table, however, it is important to address the related challenges to ensure that these collaborations are successful in achieving sustainable goals.

One of the main challenges is the communication gap between designers and scientists. These two groups often speak different languages and have different ways of thinking; another challenge is the issue of scale, environmental urgencies often require large-scale solutions that involve policy changes, infrastructure development, and systemic change and this requires collaboration with a wide range of stakeholders, including policymakers, businesses, and communities. It cannot be something only left to the designer.

Design research is a field of inquiry that focuses on understanding the design process, exploring needs, and evaluating the effectiveness of design solutions (Baskerville, Kaul and Storey, 2015). Design researchers use a variety of research methods to gain insights and inform the design process.

Science, on the other hand, is a systematic and empirical approach to understanding the natural world through observation, experimentation, and data analysis (Enyioko, 2016). Scientists use a range of tools and techniques to gather and analyse data, and they seek to develop theories and models that explain natural phenomena.

Design research and science can also inform each other (Vossen et al., 2020). For example, scientific findings can be used to inform the design of products and services, and design research can generate insights that inform scientific inquiry. In this way, the two fields can work together to create innovative solutions and advance our understanding of the world around us.

Despite their differences, design research and science share some similarities. Both fields require critical thinking, observation, and analysis. Both fields also value collaboration and interdisciplinary approaches. In recent years, there has been an increasing recognition of the potential benefits of combining design research and science to address complex challenges that require both scientific and design-based solutions (Papalambros, 2015).

The collaboration between these two fields can result in innovative and effective solutions that address complex problems in a comprehensive and holistic manner (Van Der Bijl-Brouwer, Kligyte and Key, 2021). This approach recognizes that environmental problems are often multifaceted and require a range of scientific expertise to solve. When these two approaches are combined, designers and scientists can work together to create sustainable solutions that are grounded in scientific research. For example, designers can use their skills to develop products and services that minimize environmental impact, while scientists can provide data and analysis to inform design decisions. By working together, designers and scientists can create solutions that are both environmentally responsible and scientifically sound, and that address the complex challenges posed by climate change and environmental degradation.

By using agro-industrial waste in design applications, designers and manufacturers can reduce their environmental impact, promote resource efficiency, and create innovative and sustainable products. There are several approaches to sustainable valorisation of agro-industrial waste in design. One approach is to use waste as a raw material for the production of new products. For example biodegradable packaging, building materials, or textiles.

By using waste as a raw material, designers can create products that are both sustainable and innovative and offer several advantages over traditional materials such as lower carbon emissions, improved insulation properties, and reduced dependency on non-renewable resources (Wilts, Von Gries and Bahn-Walkowiak, 2016).

Finally, another approach to sustainable valorisation of agro-industrial waste in design is to create closed-loop systems, where waste generated during the production process is reused or repurposed within the same system. For example, waste from agricultural production can be used as a source of nutrients for soil, or as feed for animals, creating a closed-loop system where waste is used as a resource rather than being discarded.

When it comes to sustainability, design research, on the other hand, may involve exploring the complex social, economic, and environmental factors that contribute to sustainability issues and identifying potential solutions through research, experimentation, and analysis (Battistoni, Nohra and Barbero, 2019).

Design research can work with science in various ways to address sustainability challenges. For example, design research can draw upon scientific research and data to inform design decisions and ensure that sustainable design solutions are grounded in scientific principles. In addition, design research can collaborate with scientists to develop and test new sustainable materials, technologies, and processes that can help address sustainability challenges.

Interdisciplinary practices related to design for sustainability are becoming increasingly important as designers are challenged to create solutions that are environmentally responsible, socially just, and economically viable. These practices involve collaboration between designers, scientists, engineers, social scientists, and other stakeholders to address complex sustainability challenges (Twenty questions about design behavior for sustainability, 2019).

One critical reflection is that interdisciplinary practices require a significant investment of time, resources, and expertise to be successful. It can be challenging to integrate multiple perspectives and disciplines into a cohesive solution, and communication and coordination can be difficult. This requires a commitment to collaboration and open communication, as well as a willingness to learn from and work with individuals from different fields (Edmondson and Harvey, 2017).

Ontologically, interdisciplinary practices involve the recognition that the world is complex and interconnected, with multiple systems and perspectives that influence each other. Interdisciplinary practitioners acknowledge that phenomena cannot be fully understood through a single lens or discipline but require multiple perspectives and ways of knowing. Epistemologically, interdisciplinary practices involve the recognition that knowledge is socially constructed and shaped by the perspectives and assumptions of different disciplines and stakeholders. Interdisciplinary practitioners acknowledge the importance of acknowledging and questioning the underlying assumptions and values that shape different ways of knowing, and seek to integrate multiple forms of knowledge into a cohesive whole (Miller et al., 2008).

In the context of design for sustainability and science in the research field, interdisciplinary practices can help bridge the gap between the different ways of knowing and approaches to problem-solving used by designers and scientists. Designers may bring a more holistic, systems-thinking approach that considers the social, economic, and environmental dimensions of sustainability challenges, while scientists may bring more empirical, data-driven approaches that can help validate and refine design solutions.

COLLABORATION BETWEEN SCIENCE AND DESIGN: A LITERATURE REVIEW

Design research has always tried to identify the differences and similarities between science and design and these efforts were particularly evident in the 1960s, in parallel with an attempt to make design a scientific discipline (Peralta & Moultrie, 2010). Although most of the literature present in this regard tends to draw clear boundaries between the two areas and underlines a substantial difference in their approaches, goals and results achieved, today it is evident that the complexity of contemporary problems is making the boundaries between science and design increasingly fading and it is fostering in fact a collaborative interaction between them able to enrich both.

Among the various contributions to the debate, Archer indicates design and science as two distinct fields and notes how design research differs from scientific research due to a different way of thinking and communicating, even though he specifies that the design approach is no less effective than the scientific one when it is applied to the resolution of specific design problems. Furthermore, although design research is not comparable to scientific research, it can successfully make use of the methods of scientific research (Archer, 1981).

Krippendorff highlights the differences between science and design, observing how the former deals with what is visible and observable, while the latter focuses on what does not exist yet and therefore is unobservable. While science seeks the truth and aims at the formulation of general rules and abstract theories, design seeks the "plausibility" of solutions and attempts to produce courses of actions (Krippendorff, 2007).

Gui Bonsiepe's contribution to the debate also tends to highlight substantial differences between the two areas. Bonsiepe notes how designers observe the world through the lens of "designability", while scientists through the perspective of knowledge. Similarly, the type of innovation they produce is different: designers' work generates products, services, experiences subject to socio-cultural dynamics, where scientists and researchers produce new knowledge. However, in terms of innovation, the approaches adopted have affinities in the way both proceed experimentally and through "tinkering", a sort of "proceeding by doing" as defined by the American philosopher Kantorovich (Kantorovich, 1993). Moreover, nowadays the complexity of the problems addressed prevents the designer from proceeding with an intuitive approach and requires a type of design activity that is constantly permeated with scientific knowledge and based on scientific bases

(Bonsiepe, 2007). At the same time, reflecting on the legacy of the Ulm School of Design, Bonsiepe notes how, if compared to the 1960s, the interest has now shifted from a scientific approach to design processes and from the attempt to integrate scientific knowledge into complex design systems to a different type of approach in which science is enriched by the categories of design and addressed through its criteria. Bonsiepe also hypothesizes a future in which the frontiers between science and design will blur, fulfilling the original ambition of the Ulm School to bring design to the nerve centres of society (Bonsiepe, 2005).

In more recent times Oxman has observed how the role of science is to explain and make predictions about the surrounding world, transforming information into knowledge; the role of design is instead that of giving shape to solutions capable of maximizing function and enhancing the human experience, transforming "utility into behaviour". In the proposed model, defined as the "Krebs Cycle of Creativity", Oxman explores the interaction between different domains - science, engineering, design and art - and places science and design as opposite one another on the circle, highlighting how the two outputs are also different: "perception and nature" in the case of science, "production and culture" in the case of design. Oxman's aim, however, is to demonstrate how the four domains analysed are deeply entangled and knowledge can no longer be ascribed or produced within rigid disciplinary boundaries (Oxman, 2016).

Echoing Oxman's speech, Ito observes how the collaboration between design and science has the potential to allow the progress of both, producing a rigorous but flexible approach to explore and understand reality. According to Ito, the fruitful interaction between design and science takes place in the context of "anti-disciplinarity", which he defines as that space that cannot be framed in any existing academic discipline and which is therefore not regulated by specific rules and methodologies (Ito, 2016).

Similarly, Rust (2004, 2007) highlights how the purpose of scientific research is discovery while that of design is invention. However, it identifies a creative dimension in scientific research to which designers can contribute and tries to define how the collaboration between science and design can be carried out.

Beyond the more evident contributions that the designer can offer to scientific research, such as the construction of representation and simulation models, the design of artifacts for tests and experiments, the conception of scenarios, the visualization of concepts and ideas and the dissemination of results, design is able to actively participate in scientific research by bringing new inputs for reflection and experimentation, finding new applications to scientific results, encouraging the pursuit of new directions for scientific research, therefore unlocking a "tacit knowledge", as defined by Rust. Rather than highlighting differences between the two approaches, Gault & Kogan (2010) consider the work of scientists and designers as complementary. Science defines the limits of technology and provides designers with the knowledge necessary to operate, while design "contextualizes" technology and repositions scientific results in new contexts, helping to open new frontiers for scientific research.

CASE STUDIES: SUSTAINABLE VALORISATION OF AGRO-INDUSTRIAL WASTE AND RESIDUES IN ACADEMIA-INDUSTRY RESEARCH

Design for sustainability requires an interdisciplinary approach that involves collaboration between experts in different fields, also including chemistry, which can play a crucial role in this approach. In fact, as sustainable design aims to create products, services, and systems that minimize negative impacts on the environment and society, chemistry can contribute to sustainable design through the development of new materials, or the optimization of chemical processes, and/or also the evaluation of products and processes environmental and health impacts (Designing safe and sustainable products requires a new approach for chemicals, 2019).

In this context, green chemistry appears to well integrate design and chemistry for sustainability, as it focuses on designing chemical processes and products that are environmentally friendly, using renewable resources, minimizing waste, reducing energy use, and preventing pollution. By using green chemistry principles, designers can create products and systems that have a reduced environmental impact.

Indeed, to date, the incentive for the use of biomass for the production of chemical compounds responds to the need of the industrial sector to comply with regulations that encourage a drastic reduction in the use of fossil fuels by limiting environmental impacts (Transition Pathway for the EU Chemical Industry. 1st edn, 2023). Therefore, the search for more sustainable alternatives, such as waste generated by agro-industry, is a beneficial approach in terms of potential renewable sources of feedstock for the production of high value-added resources such as bio-based chemicals, chemicals intermediates, biomaterials, etc. In this context, the wine sector appears to be a precious resource of biomass or waste in general, the reuse of which is fruitful. However, from the point of view of sustainability, the use of waste and residues from wine production must be accompanied by the use of sustainable processes in which it is emphasized that both the product and the process used to produce it must comply with the fundamental principles of sustainability.

The development of methodologies that allow a large-scale use, not only in the laboratory, of waste and residues becomes fundamental, as well as the shared principles of openness, transparency, reciprocity and excellence. This is in line with the aim of valorising Vitis vinifera L. leaves, which represent the least studied or valorised residue of the vine crops and wine industry, as part of a joint research project between the Department of Engineering and the Department of Environmental, Biological and Pharmaceutical Sciences and Technologies, as part of the activities of the PhD in Environment, Design and Innovation at the University of Campania Luigi Vanvitelli. The little information available on the phytochemical composition of grape leaves suggests that the content of organic acids, phenolic acids, flavonols, enzymes, vitamins, carotenoids, tannins, procyanidins, anthocyanins, lipids, terpenes and reducing and non-reducing sugars is of great interest (Maicas and Mateo, 2020). Furthermore, the leaves, unlike other residues of wine production, are not included in the DM 27 November 2008 as renewable by-products, they are waste material whose disposal during green pruning is massive (DM 27 November 2008). Solvent extraction is particularly convenient. However, traditional techniques require the use of large amounts of solvent and extended processing times to achieve optimal recovery, negatively impacting human health and the environment. With a view to sustainability, alternative extraction techniques have emerged, considered capable of reducing the amount of energy used, treatment times and eliminating, or if impossible, minimizing the use of solvents in the extraction processes, thus reducing extraction times and increasing yields and extract quality (Casazza et al., 2010). Among the latter, within the research, Supercritical Fluid Extraction (SFE) and Ultrasound Assisted Maceration (UAE) based on Deep Eutectic Solvents (DES) were of interest for the recovery of bioactives from grape leaves. In fact, it has been observed that the use of DES selectively extracts the flavonol quercetin glucuronide.

DES are classified as a new generation of ionic liquids, whose application on Vitis vinifera leaves has favored the obtainment of highly biocompatible extracts, avoiding their toxicity. In particular, the DES considered were based on water, choline chloride and citric acid. They were therefore a mixture of green and biodegradable substances, characterized by ease of synthesis, as well as low cost and high availability of raw materials (Rodríguez-Delgado, Herrera-Herrera and Socas-Rodríguez, 2021). The launch of the research and experimentation activities obtained the collaboration of the "Cantine Antonio Caggiano" winery of the Municipality of Taurasi, in Campania, Italy, for access to waste and by-products as well as receiving support for the transfer of contents and knowledge of viticulture and oenological practices. The laboratory experience was conducted at the Food Chemistry Laboratory of the Department of Environmental, Biological and Pharmaceutical Sciences and Technologies (DISTABIF). As already discussed, the solid-liquid extraction of bioactive molecules using eutectic solvents was chosen for its characteristics in line with the principles of sustainability and it was possible to isolate and identify, by means of spectroscopic and spectrometric techniques, the only metabolite quercetin glucuronide in pure form.

From a sustainability perspective, deep eutectic solvents (DES) are a viable alternative to conventional solvents and have the advantage of being more environmentally friendly than conventional solvent extraction methods. DES can be made from renewable and biodegradable materials and can be reused many times without generating as much waste or emissions as conventional solvents. Furthermore, DES, as is the case in our laboratory work, can be designed to selectively extract specific compounds, reducing the amount of energy and resources required for downstream processing. It is certain that disadvantages can also be linked to this type of extraction and further research is needed to fully understand its environmental and social impacts and develop best practices for its use. It is important to consider the entire life cycle of DES, from production to disposal, and to adopt a holistic approach to sustainability that considers the wider social, economic and environmental impacts of DES usage (Alam et al., 2021).

One of the biggest limitations of the use of DES appears to be the intimate association that parts such as citric acid, itself obtainable in a sustainable way through the fermentation of renewable sources of biomass such as corn, establish with the molecules in the extract. The removal of citric acid must also be carried out in a sustainable way but the various efforts reported in the literature do not seem to pursue this aim. The isolation procedures of the quercetin glucuronide and the removal of the citric acid were carried out effectively using gel permeation techniques.

Quercetin glucuronide is a plant-derived flavonoid and has various health benefits, including antioxidant and anti-inflammatory properties which underscore its feasibility for use in the nutraceutical and cosmeceutical sectors. Although it is mainly used in food supplements and pharmaceuticals, there are some potential applications for its use in design as well, such as natural dyes for fabrics and other materials, and its antioxidant properties can help protect these materials from damage caused by UV rays. These properties of the molecule can equally be exploited for the constitution of smart packaging materials, particularly for food and beverages. In this context, the controlled release of the molecule to the food could help extend the shelf life of the products. A further hypothesis of use is that for the development of sustainable materials, such as bioplastics and biosensors.

Overall, the use of quercetin glucuronide in design applications is still relatively unexplored, but it has the potential for use in various areas, such as natural dyes, packaging materials, cosmetics, novel foods, nutraceuticals, and sustainable materials. As with any new material, further research and development will be needed to fully understand its properties and potential applications.

The second research project considered concerns the development of innovative processes for the circularity of the textile sector, always through the valorisation of different agro-industrial wastes. The activities were carried out as a part of another PhD thesis project in the ADI PhD Course, at the University of Campania Luigi Vanvitelli. In particular, the research project investigates the possibility of using the by-products of the production of saffron (petals and stamens), wine (pomace) and oil (pomace) for the extraction of natural dyes and the development of a process of sustainable dyeing that represents a viable alternative to synthetic dyes. The experimental activities were conducted at the Food Chemistry Laboratory belonging to the Department of Environmental, Biological and Pharmaceutical Sciences and Technologies (DISTABIF) of the Luigi Vanvitelli University of Campania and at the Department of Textile Engineering of the Universitat Politècnica de Catalunya.

The case study addressed represents an example of how design can intersect with other disciplinary fields, in this case with chemical sciences and industrial engineering, in order to generate virtuous and innovative solutions in sectors, such as textiles, characterized by a high environmental impact and in need of urgent and targeted interventions.

The negative impacts of the textile sector are distributed along the entire value chain and are mainly attributable to the relevant emissions of greenhouse gasses, with over 3.3 billion tons of greenhouse gasses emitted annually along the value chain (Ellen McArthur Foundation, 2019), to the consumption and pollution of water resources -linked not only to the production phase but also to that of consumption and to the microplastics released during the washing of synthetic fibers- and to the massive production of textile waste. The difficulty in tackling the problem is also linked to the extreme complexity and fragmentation of the textile value chain, which make it difficult to adopt solutions that respond to the logic of sustainable innovation.

In this sense, observing the problem through the point of view of design is useful for restoring an overall vision that embraces the entire production chain, through a systemic and circular approach. The tools of design have proved to be fundamental in order to be able to carry out a holistic analysis (Bistagnino, 2011) of the agro-industrial chains taken into consideration and a quantitative and qualitative study of the flows of material and immaterial resources (input and output): matter and energy but also actors involved, knowledge and technologies that come into play.

Applying the design approach to the problem made it possible to identify the significant quantity of output produced by the system as a resource rather than waste, to detect potential application sectors and to connect different supply chains - the agro-industrial and the textile one -, generating a series of benefits for both. This overall vision has also made it possible to define the set of critical issues on which it is necessary to intervene and to which design collaborating with other disciplines must give an answer, such as the suitability of waste for natural dyeing production, the feasibility in terms of costs and adaptability to existing technologies and infrastructures, the scalability of the process, the performances, the environmental, social and economic sustainability of the entire process.

The contribution of chemical sciences and industrial engineering provided the necessary knowledge and know-how and was translated into the drafting of an experimental plan aimed at identifying:

- The most suitable natural dye extraction technique for each type of waste and most compatible with the identified environmental sustainability requirements
- The most suitable substrate pre-treatment technique for each of the textile fibers taken into consideration and most compatible with the identified environmental sustainability requirements
- The most suitable mordanting process (premordanting, metamordanting, postmordanting) and dyeing process and most compatible with the identified environmental sustainability requirements

HOW TO BEST IMPLEMENT INTERDISCIPLINARY APPROACHES FOR SUSTAINABILITY IN THE FUTURE?

This work concludes with considerations related to the discipline of design and interdisciplinary approaches that can promote sustainable practices for the valorisation of biomass generated by agro-industrial production.

To determine the potential for valorisation of available agro-industrial waste and residues, a comprehensive assessment of types and quantities is required. This evaluation should involve experts from different fields of knowledge, from agriculture, to food processing, to waste management.

The upstream reduction of waste and agro-industrial residues is crucial for a sustainable and innovative valorisation, the use of efficient production processes and the implementation of good practices for waste management represent a virtuous approach.

The environmental impact of agro-industrial waste and the valorisation of residues must be evaluated through a life cycle analysis. Experts from different sectors can work together to identify opportunities for improving the sustainability of the valorisation process. Life cycle assessments can be used to identify critical environmental impact points throughout a product's life cycle.

The sustainable valorisation of agro-industrial waste and residues requires collaboration and networking between stakeholders from different sectors, this practice can help designers understand the needs and values of different parties by including them in the different design phases.

The achievement of these objectives is closely linked to the presence of interdisciplinary research teams, partnerships between industry and academics and networking activities, in this context the discipline of systemic design has many virtuous cases by adopting a holistic approach and considering the entire system in which you enter a product or a process.

Further useful tools can be the analysis of the flows of matter and energy within a system, identifying inefficiencies and opportunities for improvement; user research to understand user needs and behaviours which is essential for designing products and services that are effective and sustainable, while also helping to identify opportunities for sustainable design interventions, such as encouraging lifestyle change or designing products that reduce consume.

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