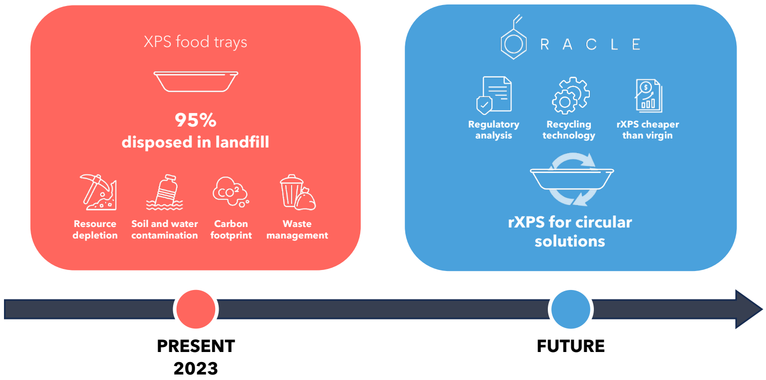
ORACLE



Graphical abstract of ORACLE project

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Executive summary

Plastic is one of the most significant innovations of the 20th century and, thanks to its versatility, it has become essential to our lives. However, each fragment of plastic we have employed or relinquished has indelibly imprinted its presence, and in recent times, there have been increasing discussions about the consequences this may have on the planet and on future generations. A closer and more comprehensive look reveals that the advantages of using this material far outweigh the disadvantages. For this reason, it is unthinkable to eliminate plastic but, rather, it is necessary to understand how to make its use more sustainable. In this sense, recycling undoubtedly plays a key role in the ecological transition. While many plastics have been following a circular economy path for years, extruded polystyrene (XPS) is hardly reused at the end of its life. This becomes a major issue considering that polystyrene is the sixth largest polymer in the world in terms of production. Indeed, the remarkable properties of this material, including lightness, flexibility, water resistance and insulation capacity, make it an ideal material for food containers and, consequently, it is widely used in packaging and disposable products. Unfortunately, these are not recycled or, at least, cannot be reused for food-contact applications. As a result, 95% of post-consumer XPS waste ends up in landfills, with a huge environmental impact. To tackle this problem, the recycling route seems to be the most reasonable one, reducing waste pollution and decreasing the production of virgin plastics, thereby safeguarding the fossil resources from which they are created. As with other plastics, recycling can be mechanical or chemical. In the case of PS, however, the high temperatures of the latter could degrade the material, and for this reason, mechanical recycling is preferred. Nevertheless, there are neither regulations nor available experimental data regarding the recycling of this material for food contact applications, unlike other plastics such as polyethylene terephthalate (PET).

In this context, a close collaboration between Alta Scuola Politecnica and GreenChemicals gave birth to ORACLE, whose name is representative of the research question: "Can pOlystyrene XPS food tRAys be recyCLEd?". Indeed, the team's goal is to respond to all these challenges through a holistic approach and to create a comprehensive and sustainable solution. This, by meticulously exploring the technical and regulatory aspects of the problem, and then designing a feasible and efficient recycling process for XPS. The ultimate aspiration is to secure approval from the European Food Safety Authority (EFSA), allowing the recycled polystyrene to be safely utilized in food contact applications.

With this initiative, ORACLE is committed not only to the mitigation of the environmental impact of plastic waste but also to the contribution to the circular economy model. Given the significant regulatory and technological gaps that the project seeks to bridge, the team have structured its work into two basic and distinct phases. As a first step, it was necessary to understand what regulations and regulatory procedures govern plastic recycling processes, particularly in the food packaging sector. Since there are no specific information regarding PS recycling, during the first few months the ORACLE team analysed the official documentations related to recycled plastic materials and articles intended to come into contact with foods (EC regulations 2022/1616 and 1935/2004) taking them as a reference to understand both the requirements in terms of contaminant threshold values in recycled material as well as the bureaucratic procedure to follow when proposing a new technology. Once this was clarified, the technological process for recycling XPS was defined through a collaboration with Gamma Meccanica. Specifically, an efficient method for removing contaminants from post-consumer XPS packaging was identified using supercritical CO_2 injected into the recycling line.

For the reintroduction of recycled plastic in contact with food, the focus of the process is on the decontamination from hazardous substances. Nevertheless, the establishment of a definitive collection and sorting system for XPS remains pending. Therefore, the acquisition of post-consumer material has been facilitated through the efforts of Gruppo Happy, who has undertaken a dedicated collection initiative. After this collection process, the postconsumer material has undergone an artificial contamination due to the introduction of appropriate substances as part of the procedural steps, at Gamma Meccanica's facilities.
Once pollutant levels compatible with those in the waste were reached, extrusion and decontamination using CO_2 were carried out. Measurements at the end of the process, aimed at quantifying the efficiency of pollutant removal, demonstrated the feasibility of the process. Moreover, it was shown through an economic analysis that the specific cost (€/kg) of recycled XPS was fairly lower than that of virgin material, making the recycling route worthwhile not only environmentally but also economically. Although significant decontamination progress has been made, the current efficiencies are insufficient for obtaining EFSA certification. Furthermore, given the lengthy 42 to 78-month certification process timeline, alternative non-food sector applications for recycled XPS were identified. Indeed, Swisspor conducted tests for insulation panel production, and in collaboration with Selit, they explored underfloor layer applications using recycled XPS. The tests provided a positive outcome and proved the process to be already capable of producing a secondary raw material suitable for the utilization in the construction sector. All in all, in a world facing the problem of creating a sustainable future, the ORACLE project shed light on the feasibility of XPS recycling, offering a tangible technological solution. In particular, the results obtained through the process confirmed that the project is on the right track, confirming CO_2 technology as probably the most suitable technology for XPS mechanical recycling. The decontamination rates downstream of the process are undoubtedly promising, although not yet sufficient to obtain the certification that would allow the material to be reused for food contact. At the same time, it would be unthinkable to obtain definitive results only after the first experimental trials. For this reason, further tests are planned for the future, in which the optimal number of degassing operations, pressure and CO_2 flow rate will be defined, with the ultimate goal of applying to EFSA for certification and finally giving new life to the polystyrene material.

Key Words

Extruded polystyrene (XPS), Recycling, Food contact applications, Circular economy

Project description written by the Principal Academic Tutor

Polystyrene (PS) is one of the most commonly used thermoplastics and it is largely used in the food packaging. It is entirely non-biodegradable and it is very important to recycle it due to the ecological impact it can have. Its lightness makes difficult its sorting from curbside containers; because it's bulky and it's difficult and expensive to transport. Therefore, many municipal recycling programs do not accept it. The polystyrene industry claims a recycling rate of about 12 percent, although recycled PS cannot be used for food contact, and this strongly limits its application after recycling.
The ORACLE project aims to perform a very complete study on the possibility to recycle the so-called extruded polystyrene (XPS). Starting from the most homogenous waste material (like food trays), the first objective is to understand the state of the art of regulation for food contact R-PET and propose to European Food Safety Authority (EFSA) a similar one for R-XPS, providing an almost-complete contaminants list and contaminants level present in the waste and proposing food approval limits. The second objective is a feasibility study for PS recycling, demonstrating in particular the possibility to completely removal volatiles and high MW contaminants to obtain XPS usable again in food packaging (on the basis of the well-known process for R-PET), and a techno-economic analysis considering all possible aspects involved in the recycling process.
The expected results of the ORACLE project are to understand the feasibility from regulatory and technical point of view of project and to understand the time plan for getting a positive opinion by EFSA and a reasonable production cost/kg.
The innovation of the ORACLE project lies on the circular economy approach of the process and on the possibility to save material from waste, reducing impact on environment.

Team description by skill

The ORACLE multidisciplinary project displays a certain homogeneity in its team members. As a matter of fact, all the collaborators have had a strong educational background in engineering. Out of the five team members, three are chemical engineering students while the remaining two members are enrolled in mechanical engineering programs. Among them, Gian Marco Potros Beshara holds the position of team leader, while Francesca Macchioni is the budget controller. Here is provided a list of the participants, together with insights on their area of expertise.

Chemical Engineers

Gian Marco Potros Beshara (Polytechnic of Milan)
Skills and expertise: Catalysis for sustainable chemistry, Unit operation design, Project management.

Federico Fiore (Polytechnic of Turin)
Skills and expertise: Power-to-Gas technologies, Life Cycle Assessment, Waste valorization.

Davide Cavuto (Polytechnic of Milan)
Skills and Expertise: Electrochemistry for chemical synthesis, Chemical reaction engineering, Computational fluid dynamics.

Mechanical Engineers

Francesca Macchioni (Polytechnic of Milan)
Skills and Expertise: Additive manufacturing, Metal 3D printing, Sustainability analysis of mechanical processes.

Francesco Amodio (Polytechnic of Turin)
Skills and Expertise: Multibody simulation, Driver assistance system, Motion planning.

The group present the ideal blend of competences needed to tackle the technical challenges of the Oracle project. If from one side the mechanical engineers have brought on the table their proficiency in handling the machinery aspects of the project, from the other side the chemical engineers have integrated their knowledge in process engineering to identify the crucial operational parameters governing the performances of the process.

Goal

Polystyrene (PS) is a versatile material known for its strength, lightness, flexibility, and water-resistant properties. Today, it has found widespread use as insulation material for food containers, hence the importance of recycling it. The problem here is that the current situation lacks a structured supply chain for PS recycling, both from a technical and legislative perspective. This is where the ORACLE project comes in, with the aim of shedding light on the crucial components needed to create a solid foundation. It all begins with a simple question: can polystyrene food trays be recycled?

The primary objective of this project is to conduct an exhaustive analysis of the procedures essential for creating an authorized recycling supply chain specifically designed for food contact applications. The goal is to outline the precise steps required to enable the certified recycling of XPS (Expanded Polystyrene) using a standardized process. Concurrently, these considerations should be complemented by a market analysis, which will be instrumental in evaluating the potential influence of recycled XPS on the economic landscape, giving emphasis on the comparison between the price of the recycled material with respect to the virgin one. This holistic approach ensures a thorough assessment of the initiative's feasibility from all perspectives.

In detail, upstream of everything, the objective of the ORACLE project can be split in two categories, addressing regulation and technology, both pushed by the need of valorizing a previously unrecycled stream. The project aims to understand the state of the art of the current regulation to obtain the food-contact certification for plastic materials. It is also important to understand how to approach the relevant bodies. In the European Union, the competent authority is the EFSA (European Food Safety Authority), whose role is to monitor food safety, serve as an impartial source of scientific knowledge throughout the food chain, and provide precise instructions on the required procedures. As already mentioned, in tandem, the ORACLE project also aims to understand which technologies can be ultimately integrated into an XPS recycling process, identifying potential solutions and configurations. In this context, analyzing the state of the art of the most common recycling technologies used for other plastic materials has played a pivotal role from the very beginning of the process, as it is a way to discover processes that are already well-known and can potentially be adapted to XPS.

Understanding the problem

Every year, 50,000 tonnes of XPS are produced in Europe exclusively for food packaging [1]. Considering the European population, this translates in to 48 g per person per day. Due to its excellent properties and widespread use, the demand for this material is projected to increase: an annual growth rate of 8.31% is expected between 2023 and 2028 [3]. Unfortunately, considering the very low density of the material, the volume of material to be disposed will also be greater. Therefore, although XPS has a multitude of advantages, the significant environmental impact associated with both its production and disposal cannot be ignored.

Indeed, while other widely used styrene-based plastics already have globally established recycling processes, XPS remains an exception. This material, which is mainly used in the construction industry (e.g., insulation panels) and in the production of food packaging, follows a life cycle that leads to the disposal of about 95% of the post-consumer material in landfills. Furthermore, due to its high calorific value, XPS cannot be incinerated as it would lead to excessively high temperatures during the process. All this rules out an end-of-life alternative that would at least have included energy recovery.

It is clear that so far this material has a linear lifecycle, continuously leveraging on fossil resources that are known to be non-renewable.

Making matter even more difficult, XPS food trays are among the main contributors to the rampant problem of marine pollution. By 2050, in fact, the oceans will contain more plastic than fish (in terms of weight) [2], causing the alteration of delicate marine ecosystems and the release of microplastics.

Importantly, the impact is not only environmental but also social and economic. The former is closely related to water and air pollution that leads to worsening living conditions and the emergence of diseases. On the economic side, the inability to recycle the material greatly increases the cost of disposal at the end of its life.

Having set the scenario, it is clear that, at present, the XPS production system is not sustainable at all: a change of route is needed.

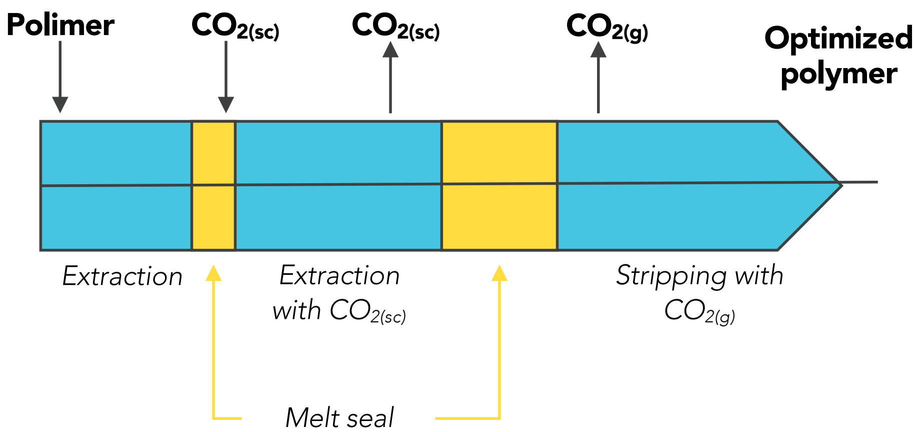
In addition to the environmental concerns mentioned earlier, there is a lack of adequate regulation preventing the plastic industry from achieving true circularity. Detailed guidelines for the development of officially approved recycling technologies are conspicuously absent. Furthermore, recycled plastics often come at a higher cost compared to virgin materials, creating an economic burden that hampers competitive viability.

Sustainable Development Goals (SDGs) associated with the ORACLE project.

Exploring the opportunities

This identified societal need presents an opportunity for the development of a business focused on mitigating the environmental impact of XPS products. In accordance with the European Waste Hierarchy, the most commendable approaches to waste pollution prevention involve prevention itself, reuse, and recycling. Among these, recycling hold particular promise for plastic streams, which are often contaminated and challenging to reuse without an appropriate recycling process. Despite the existing challenges, it could be technically feasible to recycle XPS, with several viable options available for establishing an efficient recycling pathway. Recycling can be categorized in two primary methods: mechanical and chemical. In mechanical recycling chemical reactions does not occur, and the removal of contaminants relies on the utilization of extractive solvents, stripping agents, and heating equipment, all of which leave the plastics' chemical composition unchanged. On the other hand, chemical recycling involves chemical reactions that ideally transforms the plastic back into its constituent functional units, commonly known as monomers. It is worth noting that the chemical route poses some complexities when applied to XPS due to the necessity for exceptionally elevated temperatures, which can result in the degradation of the polymer before meaningful chemical reactions can take place.

Given the above-described scenario, it is evident how the damages caused by XPS pollution are associated to a lack of organisation and resourcefulness of the plastic industry, and at the same time recycling is absolutely feasible for XPS. In this "soft spot" the ORACLE team tried to both satisfy a need that regards the whole society and to develop an entrepreneurial pathway that involves XPS recycling.



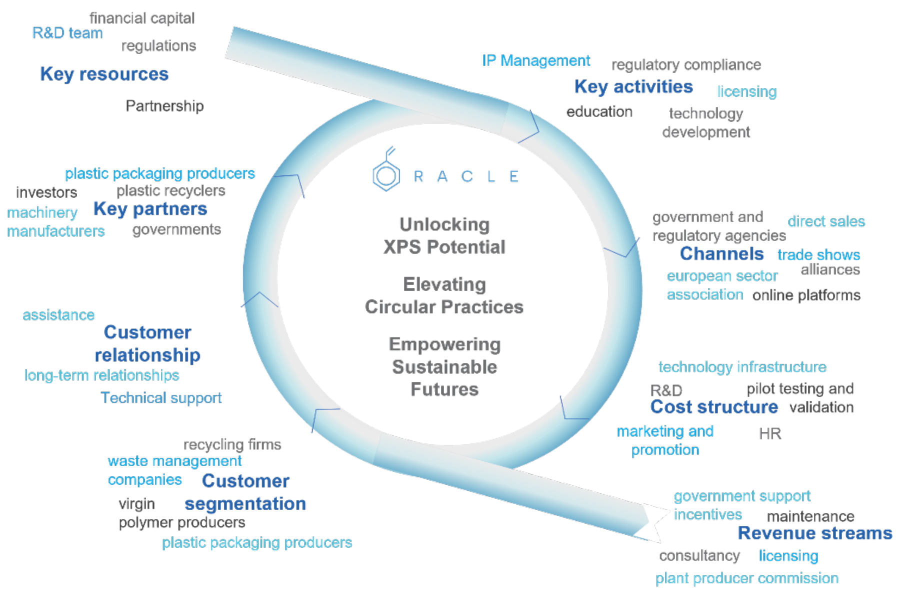
Schematic diagram of Supercritical CO_2 decontamination process for XPS recycling.

Generating a solution

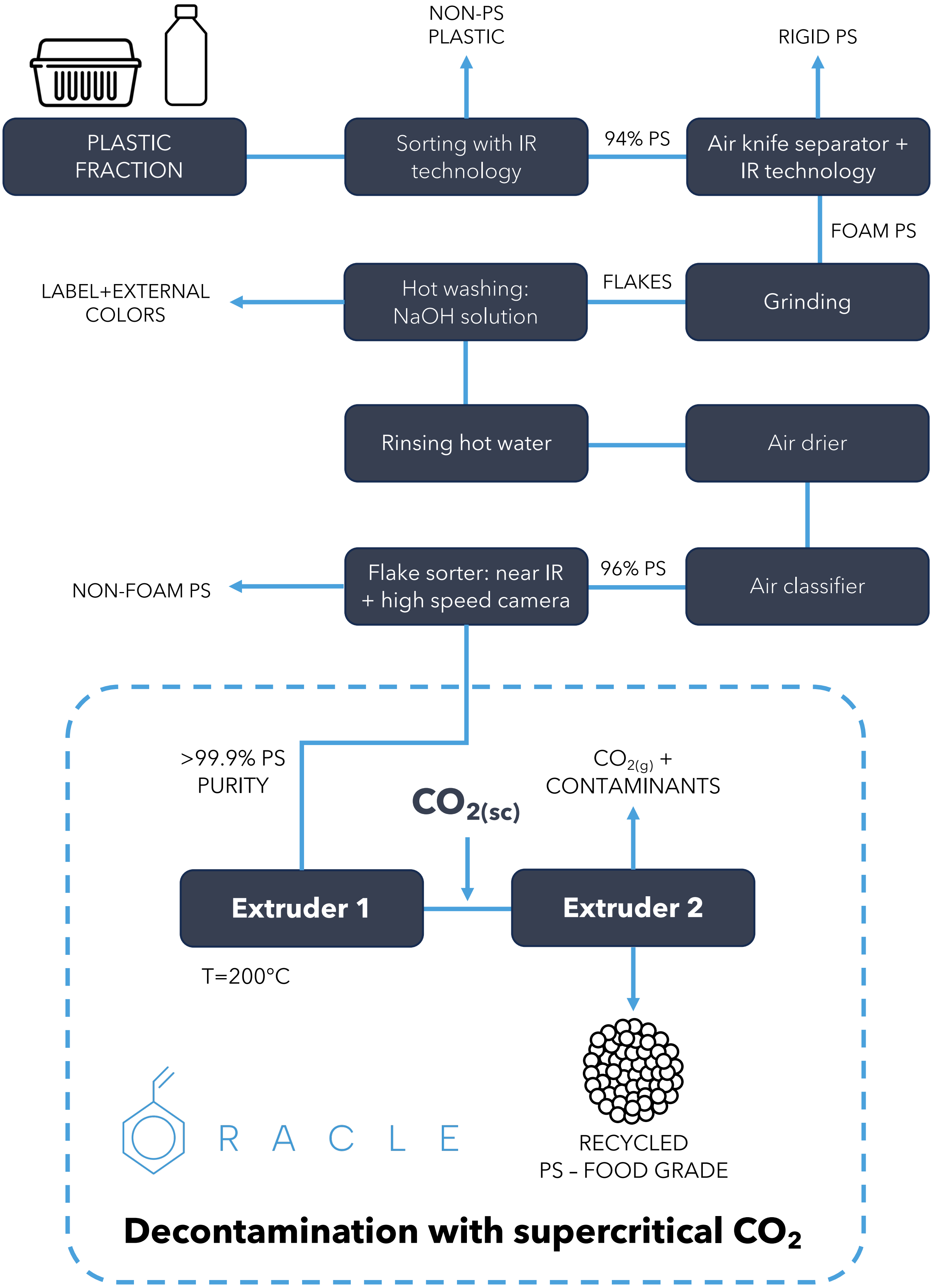
In order to stimulate research and development efforts in the field of recycling technologies and processes, it is imperative to establish regulatory frameworks that provide support to developers throughout their endeavors. Presently, there exists a notable absence of specific regulations pertaining to the recycling of XPS, a situation shared with numerous other plastic materials. Recognizing this need, a comprehensive review of extant legislation concerning plastic material recycling was conducted by ORACLE, with a particular emphasis on those intended for food contact and considering EFSA guidelines related to the mechanical recycling of PET. The outcome of this analysis culminated in the formulation of a streamlined procedure intended to guide recycling technology and process developers in their quest to secure approval from EFSA.

This procedural framework obviates the necessity of navigating the intricate bureaucratic landscape associated with plastic material recycling for food applications, thereby fostering innovation within this sector.
At its core, the solution is centered around the pursuit of a technology capable of producing recycled materials suitable for food contact purposes. In collaboration with GreenChemicals and Gamma Meccanica, the ORACLE team has successfully devised an efficient methodology for eliminating contaminants from post-consumer XPS packaging. This innovative approach involves the strategic injection of supercritical CO_2 into the recycling process, effectively purging the molten plastics of impurities. To the best of the authors' knowledge, Fraunhofer is the sole institution currently engaged in analogous research efforts.
Subsequent measurements performed at the conclusion of the performed tests on this technology, confirmed the feasibility of pollutant removal, although it fell short of meeting EFSA's certification requirements. Nevertheless, the analysis indicated the suitability of the process for non-food applications. Swisspor conducted tests for insulation panel production, and in collaboration with Selit, exploration of underfloor layer applications employing recycled XPS was undertaken. These tests yielded positive results, affirming that the ORACLE process is already capable of generating a secondary raw material meeting cleanliness and polymer quality standards for use in the construction sector. Moreover, given the protracted certification process timeline of 48 to 92 months, non-food applications emerge as a viable solution for promptly diverting XPS food tray materials towards a circular economy.

In response to the cost-effectiveness challenges associated with certain recycled plastics, as R-PET, which often exceed the costs associated with virgin materials, a comprehensive economic analysis was conducted by the team, with a focus on scaling the process to an industrial level. The results of this analysis revealed that the specific cost per kilogram (€/kg) of recycled XPS is significantly lower than that of virgin material. This significant finding not only underscores the environmental advantages inherent in the ORACLE recycling approach but also firmly establishes its economic viability. Consequently, this economic analysis confirms that ORACLE is not merely an environmentally responsible choice; it is also a prudent financial decision.
Recognizing the potential competitiveness of the process, both environmentally and economically, the decision was made to formulate a business plan to attract investors to the project. Key resources include the establishment of an XPS sorting facility, financial capital, and strategic partnerships, particularly with an extruder manufacturer. The prospective clientele encompasses a broad spectrum of stakeholders within the packaging and recycling industries. Primary expenditures are expected to be directed towards pilot testing, validation, subsequent marketing, and promotional activities. However, these outlays are anticipated to be more than offset by revenues derived from various sources, including licensing fees for our proprietary technology (subject to a royalty of 0.05 € per kg), plant producer commissions (ranging from 5% to 10% of the total plant price), consultancy services, and maintenance contracts.
Redefining waste as an opportunity for sustainable solutions.



ORACLE- Graphical representation of the Business Plan.



ORACLE XPS recycling process.

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