ASSESSING THE POTENTIAL IMPACT OF THE EUROPEAN UNION'S PACKAGING AND PACKAGING WASTE REGULATION (PPWR) ON U.S. SPECIALTY CROP EXPORT AND THE RECYCLING OF POLYPROPYLENE CONTAMINATED WITH BIOPLASTIC POLY(3-HYDROXYBUTYRATE)

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ABSTRACT

This study addresses two critical areas related to the European Union's newly approved Packaging and Packaging Waste Regulation (PPWR): first, to create a Compliance Assessment Tool (CAT) designed to evaluate the risks and threats U.S. specialty crop exporters might face when exporting to the EU under the new regulations. Second, it aimed to assess the impact of poly(3-hydroxybutyrate) (PHB) contamination on the mechanical recycling of polypropylene (PP) packaging, considering the PPWR's emerging requirements for biodegradable plastics. The successful application of the developed CAT demonstrates its effectiveness as a vital resource for identifying and addressing risks. Our findings indicate that U.S. specialty crop exporters may encounter compliance issues concerning the recycled content and recyclability requirements of the PPWR, particularly in transport packaging systems. Transport packaging systems are more complex due to the variety of materials used, making adherence to the regulations more difficult. The developed tool can be a vital resource, assisting exporters in optimizing the risk assessment process for packaging compliance. The second segment of the study revealed that while PHB contamination did not markedly hinder the technical procedures of shredding, washing, or extrusion, it did cause slight issues during the flotation phase, where small traces of PHB flakes remained in the PP float fraction. More importantly, during the extrusion and pellet characterization phases, PHB contamination affected specific material properties: the recycled PP+PHB pellets showed changes in color and odor, along with alterations in mechanical properties, such as the melt index and ash content, which exceeded the acceptable limits compared to virgin PP. While tensile modulus, stress at yield, and elongation at yield remained within acceptable limits, the tensile stress and elongation at break were below the acceptable threshold. This indicates a possible compromise in material quality when packaging converters process PHB-contaminated PP for use as recycled material.

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CHAPTER 1: INTRODUCTION

1.1 Background

Packaging is vital in ensuring the preservation, safe transport, and secure storage of products within the global market. Beyond mere containment, packaging protects items from physical damage, contamination, and degradation, thereby extending their shelf life and maintaining quality, and consequently, for the food sector, reducing food waste. Packaging design optimized for transportation ensures that goods reach distant markets in optimal condition, enhancing the potential for successful trade relationships and global commerce. The integral role of packaging in the global economy is reflected in the upward trajectory of the packaging market. In 2016, world packaging sales at current prices increased from $845,220 million to $953,706 million in 2019, representing an average annual growth rate of 4.1% (Platt, 2021). The forecast for 2021–26 remains optimistic, with world packaging sales expected to grow at an average yearly rate of 3.9%, reaching $1,229,619 million (Platt, 2021).

The modern packaging industry has traditionally followed a linear economic model characterized by a “take, make, dispose” approach. This model, driven by the need to meet the demands of a growing global population, involves extracting raw materials, manufacturing products, and disposing of them post-use (Ellen MacArthur Foundation, n.d.; Pearce & Turner, 1989). Such practices have led to significant environmental issues, including natural resource depletion and waste accumulation. In response, there is a strong movement towards applying circular economy principles. The circular economy model, conceptualized initially by Pearce and Turner (1990), strives to eliminate waste by maintaining products in use as long as possible through strategies like reuse, maintenance, recycling, and composting. This approach helps preserve finite resources and reduce waste.

Governments have actively promoted regulations and incentives to transition towards a more circular economy. This push is primarily driven by growing consumer concerns about the environmental impacts of packaging waste, particularly single-use packaging. In response, there has been a significant increase in legislation aimed at reducing packaging, targeting substrates, and improving waste management.

These new policies adhere to the principles of the circular economy by encouraging companies to design packaging that reduces material use, enhances reusability and recycling, and incorporates recycled content.

A notable regulatory advancement is the updated European Packaging and Packaging Waste Regulation (PPWR), which imposes stricter standards for packaging used within or imported to Europe. The PPWR mandates reductions in packaging volume and weight-packaging minimization, enhancement of reusability, increase in recycling rates and the use of recycled materials, elimination of hazardous substances, and improvement of labeling practices (European Parliament, 2024). It also strengthens extended producer responsibility (EPR) schemes to ensure producers are accountable for their packaging throughout its life cycle (European Parliament, 2024).

Similarly, other world regions are advancing regulations to address plastic waste. In Canada, the government has published proposed measures to facilitate the further management of its plastic waste. These measures include requirements for minimum recycled content, labeling of recyclable and compostable plastics, and a mandate for all packaging to be 100% reusable, recyclable, or compostable by 2028 (Environment and Climate Change Canada, 2023). The United Nations Environment Programme (UNEP) has endorsed resolutions establishing a legally binding global agreement to manage plastics. This agreement would propose regulations on recycled content inclusion in packaging, packaging minimization, design for recycling and reuse, and prohibitions on harmful substances (United Nations Environment Programme, 2023). With 193 countries as part of the UN, countries adhering to this treaty could significantly increase and expand new packaging regulations globally.

1.2 Research Problem

The forthcoming regulations concerning packaging waste centered around the principles of the circular economy, introducing a degree of ambiguity for most stakeholders in the supply chain, particularly regarding their potential implications for international trade and what the future could mean for plastics and bioplastics.

1.2.1 The PPWR: Compliance Challenges for U.S. Specialty Crop Exporters

The European Union (E.U.) is a significant trading partner for the United States (U.S.) in agricultural goods, including specialty crops. In fiscal year 2021, the export value for U.S. specialty crops increased from $23.7 billion in 2020 to $24.9 billion in 2021 (United States Department of Agriculture, 2022). The E.U. accounted for 15.5% of total U.S. exports, with total U.S. exports to the E.U. amounting to $271.6 billion in 2021 (U.S. Department of Commerce, 2022). Within the agricultural sector, the EU was the fifth-largest export destination for U.S. agricultural products, and the U.S. ranked as the third top supplier of agricultural goods to the EU (USDA Foreign Agricultural Service, 2022).

The new PPWR introduced in the European Union (EU) establishes a set of specific requirements for packaging that aim to enhance sustainability and reduce environmental impacts. These new regulations may pose significant challenges for U.S. exporters, particularly those involved with specialty crops, because of the stark differences in regulatory standards between the United States and the European Union. The divergence in packaging requirements can lead to substantial barriers to trade. U.S. exporters might risk their products being rejected at EU borders due to non-compliance with the new EU standards. Such rejections can tarnish exporters' reputations and lead to potential financial losses, as goods may need to be re-packaged or returned. Therefore, it is crucial for U.S. exporters to closely observe these new regulations and possibly adapt their packaging processes to navigate the complexities of the EU market successfully.

However, understanding and interpreting the legislative text of such regulations can be challenging due to the complex legal language, technical requirements, and frequent updates. These complexities, along with differences in regulatory frameworks between regions, can make it difficult for companies to ensure full compliance with new standards.

To address this challenge, this thesis developed a Compliance Assessment Tool (CAT) to help U.S. specialty crop exporters evaluate their packaging in relation to the new Packaging and Packaging Waste Regulation (PPWR). The tool simplifies the compliance process by outlining the key requirements and offering an easy-to-follow guide for companies to modify their packaging accordingly. By using this proactive approach, exporters can decrease the chances of their products being rejected at EU borders,

facilitating smoother market access and minimizing potential financial losses, thereby improving their competitive edge. To the researchers' knowledge, this is the first tool of its kind developed for the packaging industry.

1.2.2 The PPWR and new requirements for biodegradable plastics

Another significant concern within the framework of this regulation is the introduction of stringent requirements for biodegradable plastics. Specifically, Article 8 of the Packaging and Packaging Waste Regulation (PPWR) stipulates that "...packaging made of biodegradable plastic polymers shall allow for material recycling without affecting the recyclability of other waste streams" (European Parliament, 2024).

While this requirement is intended to enhance the circularity of bioplastics, it introduces technical challenges as the impact of some biodegradable plastic polymers, such as polyhydroxyalkanoates (PHAs), on mechanical recycling processes is not yet thoroughly understood or documented (Alaerts et al., 2018; Kumar et al., 2023). This knowledge gap can impede effective recycling and sorting processes, potentially compromising the properties of recycled plastics.

Poly(3-hydroxybutyrate) (PHB), one of the most researched and commonly used types of PHAs, has attracted considerable interest in the packaging sector due to its renewable origin from organic waste and non-food crops, its biodegradability in different natural settings, its excellent oxygen, moisture, and UV barrier properties, and its mechanical characteristics that closely resemble those of traditional petrochemical plastics like polypropylene (PP) (Dhaini et al., 2024; Garcia-Garcia et al., 2022; Gonzales-Rojo et al., 2024).

Its comparable mechanical performance and excellent barrier properties position PHB as a viable candidate for replacing and complementing traditional plastics in diverse packaging applications. However, its compatibility with existing recycling streams is a significant challenge, particularly with widely used polymers such as PP. This uncertainty concerning recycling infrastructure may impede the broader adoption of PHB in packaging solutions, especially in jurisdictions where stringent recyclability standards are mandated.

This thesis aims to evaluate the influence of PHB contamination on the mechanical recycling of rigid PP. It specifically investigates the extent to which the presence of PHB alters the mechanical properties and overall quality of recycled PP. Understanding this relationship is vital for assessing the compatibility of PHB with conventional plastics in adherence to the requirements of the PPWR, while ensuring the integrity of the circular economy for plastic packaging streams.

1.3 Objectives

The study seeks to tackle the challenges introduced by the European Union's newly approved PPWR, by focusing on two key sub-objectives:

- To develop a Compliance Assessment Tool (CAT) to evaluate the risks and threats associated with exporting major U.S. specialty crops to the European Union, particularly in response to the newly approved PPWR.
- To assess the potential impact of poly(3-hydroxybutyrate) on the mechanical recycling of polypropylene packaging in response to the new biodegradable plastics requirements under the PPWR.

1.4 Thesis Outline

The thesis is structured as follows:

- Chapter 1: Introduction – This chapter outlines the central research issue, highlighting the compliance challenges that U.S. specialty crop exporters may face due to the recently approved PPWR and its potential trade impacts. It also briefly overviews the complex issues surrounding biodegradable plastics linked to the recently enacted PPWR.
- Chapter 2: Literature Review – This chapter reviews literature on existing and emerging packaging regulations and how this can impact international trade. It also discusses compliance assessment tools and how this can help ease packaging assessment and regulatory compliance. The review also delves into the literature on PP and its recycling and PHB. Additionally, it discusses empirical studies addressing the issue of compostable plastic contamination within the recycling stream.

- Chapter 3: Methodology – This chapter outlines the methodology used in the thesis. It details the development of the Compliance Assessment Tool for U.S. exporters and the experimental design for studying PHB's impact on the mechanical recycling of PP.
- Chapter 4: Results & Discussion—This chapter provides the study's findings and relates them to the broader regulatory and economic landscape.
- Chapter 5: Conclusion & Recommendations for Future Research—This final chapter summarizes the study's main findings and identifies areas for future research.

CHAPTER 2: REVIEW OF LITERATURE

2.1 Overview of current and emerging packaging waste legislation

The evolution of packaging regulations over the past century reflects a substantial transformation in the legislative landscape governing product quality and consumer safety. Early laws, such as the U.S. Pure Food and Drug Act of 1906 and the U.S. Fair Packaging and Labeling Act of 1966, primarily aimed to ensure that products were safe and labeled correctly. As industrialization led to more widespread packaging use, especially of single-use plastics, environmental concerns rose, shifting the regulatory focus. In the mid-20th century, heightened pollution awareness prompted governments to consider environmental impacts, which set the stage for regulations to reduce packaging waste.

Table 2.1 outlines various regulatory measures regarding packaging waste from selected countries and states, organized into key regulatory trends. These measures are typically classified into the following categories:

Packaging prohibitions: This involves bans on specific packaging types such as polystyrene (PS) containers, several single-use packaging formats, and polyvinyl chloride (PVC) containers due to their recycling challenges. Further, it includes bans on packaging with intentionally added substances of concern (e.g., PFAS (per- and poly-fluoroalkyl substances), BPA (bisphenol A), as well as limitations on the concentration levels of certain compounds in packaging materials (e.g., lead, cadmium, mercury) (ME LD1503, 2021; CA AB1200, 2021; European Parliament, 2024).

Promotion of reuse and refill strategies: Several countries are encouraging the increase in the share of reusable packaging placed on the market and of systems to reuse packaging in an environmentally sound manner. Such measures include deposit-return schemes and setting quantitative targets for a minimum percentage of reusable packaging placed on the market for each packaging stream (WA SB5323, 2020; Environment and Climate Change Canada, 2023; Oregon Department of Environmental Quality, 2007).

Emphasis on achieving recyclability and increased recycling: Numerous countries are intensifying efforts to enhance the recyclability of packaging materials and boost overall recycling rates. These

initiatives include setting standardized specifications for the structure of the packaging material to facilitate ease of recycling (Blank & Gregor, 2024; Song & Park, 2024; Steinhorst & Beyerl, 2021).

Requiring packaging to have minimum recycled content: Certain countries enforce regulations mandating packaging to contain a minimum proportion of recycled material, aiming to drive demand for a healthy post-consumer recycled (PCR) market, reduce reliance on virgin materials, and divert waste from landfills (European Parliament, 2024; C. Lee et al., 2024; CA AB793, 2020).

Extended producer responsibility (EPR) programs: EPR legislation continues to expand in several areas of the world and is gaining momentum (Enders et al., 2024; WA SB5154, 2024). These initiatives hold producers accountable for the end-of-life management of their products, encouraging them to take responsibility for recycling and disposal (Lorang et al., 2022).

Table 2.1 Selective cross-country comparison of legislations addressing packaging waste.

Country / State	Packaging Prohibitions	Recycling Targets	PCR Requirements	Reuse/ Refill Mandate	EPR Obligations	Other Requirements
			North America			
United States (US) / California	California Assembly Bill 1200, enacted in 2021, bans the distribution or sale of any food packaging that contains regulated PFAS in the state of California (CA AB1200, 2021). California Senate Bill 270, enacted in 2014, prohibits stores from providing single-use carryout bags, and recycled paper bag or compostable bags unless made available for purchase for not less than $0.10 (CA SB270, 2014).	California Senate Bill 54, enacted in 2022, requires that by 2032 all single-use packaging/ plastic food service ware be recycled after use. To work up to the 2032 targets, 30% of packaging needs to be recycled by January 1, 2028, and 40% by 2030 (CA SB54, 2022).	California Assembly Bill 793, enacted in 2020, requires plastic beverage containers to contain no less than 15% PCR by Jan 2022: 25% by Jan 2025, and 50% by Jan 2030 (CA AB793, 2020). California Senate Bill 270 (2014) mandates that standard recycled paper bags contain at least 40% post-consumer recycled (PCR) material, or 20% PCR for bags carrying eight pounds or less. It also requires reusable plastic grocery bags to have a minimum of 40% PCR material and to be recyclable in the state (CA SB270, 2014).	California Senate Bill 270 (2014) only allows use of reusable bags from certified reusable grocery bag producers. These reusable bags should be reusable at least 125 times, capacity of at least 15 liters, cleanable, labeled, does not toxic materials, and if recyclable, complies with recycling guidelines (CA SB270, 2014).	California SB 54 (2022) directs producers to create a Producer Responsibility Organization (PRO), and to design, fund, and operate a statewide program that properly collects and recycles, or composts discarded products (CA SB54, 2022).	California SB 343, enacted in 2021, prohibits the use of the chasing-arrows symbol on products that are not recyclable (CA SB343, 2021).
US / Colorado	Colorado House Bill 1162, passed in 2021, prohibits stores and retail food establishments from providing single-use carryout bags and expanded polystyrene (EPS) cups and containers to customers (CO HB1162, 2021).	The Colorado Solid and Hazardous Waste Commission adopted a statewide municipal solid waste diversion goal of 35% by 2026, and 45% by 2036 (State of Colorado, 2024). No specific state-wide packaging recycling targets were identified.	No specific PCR requirements for packaging were identified.	No specific reuse/refill mandate for packaging were identified.	Colorado House Bill 1355, passed in 2022, requires the appointment of a nonprofit organization to implement and manage a statewide recycling program, funded by producers of products that use packaging materials and paper products (CO HB1355, 2022).	

Table 2.1 (cont'd).

Country / State	Packaging Prohibitions	Recycling Targets	PCR Requirements	Reuse/ Refill Mandate	EPR Obligations	Other Requirements
			North America			
US / Connecticut	Connecticut House Bill 7424, passed in 2019, banned the provision and sale of single-use plastic bags with thickness of less than 4mils to customers at the point of sale (CO HB7424, 2019). Connecticut Senate Bill 837, passed in 2021, prohibits the sale of food package to which PFAS has been intentionally added (CT SB837, 2021).	Connecticut's 2016 Comprehensive Materials Management Strategy (CMMS) targeted a 60% diversion of materials from disposal by 2024 (Connecticut Department of Energy & Environmental Protection, 2023). No statewide packaging recycling targets were identified.	Connecticut House Bill 6664, passed in 2023, requires plastic beverage containers to have 25% PCR content by 2027, and 30% by 2032 (CT HB6664, 2023).	No specific reuse/refill mandate for packaging were identified.	Connecticut House Bill 6664, passed in 2023, creates a registration program for producers of plastic beverage containers beginning April 2026 (CT HB6664, 2023).	
US / Illinois	Illinois in January 12, 2024 proposed House Bill 4448, which prohibits any store or food service business from providing single-use plastic carryout bags to customers (IL HB4448, 2024). Illinois House Bill 3865, proposed on February 17, 2023, prohibits the sale and distribution of polystyrene foam food service containers (IL HB3865, 2023). Illinois Senate Bill 88, proposed on January 20, 2023, prohibits the sale and distribution for use of food packaging containing intentionally added PFAS (IL SB88, 2023).	The Illinois Solid Waste Planning and Recycling Act aims to recycle 25% of all waste generated for each county (Illinois Environmental Council, n.d.). No statewide packaging recycling targets were identified.	Illinois SB1555 (Packaging and Paper Products Stewardship Act), passed in 2023, requires each producer to achieve a PCR content of 15% by 2028, 25% by 2031, and 50% by 2034 in the rigid plastics it produces (IL SB1555, 2023).	Illinois SB 1555 requires producer or producer responsibility organizations acting on the producer's behalf, to propose reuse and recycling rates, and a description of how they will meet or exceed these targets (IL SB1555, 2023).	Illinois SB1555 requires that by July 1, 2026, no producer shall sell or distribute unless the producer or producer responsibility organization acting on the producer's behalf, has a 5-yr program plan approved by the Illinois Environmental Protection Agency for meeting the requirements of the Act (IL SB1555, 2023).	

Table 2.1 (cont'd).

Country / State	Packaging Prohibitions	Recycling Targets	PCR Requirements	Reuse/ Refill Mandate	EPR Obligations	Other Requirements
			North America			
US / Maine	Maine House Bill 289, passed in 2019, prohibits the distribution of disposable food service containers composed in whole or in part of polystyrene foam (ME LD289, 2019). Maine House Bill 1503, passed in 2021, prohibits the sale and distribution of any product that contains intentionally added PFAS (ME LD1503, 2021).	Maine's goal is to recycle or compost 50% of the municipal solid waste tonnage generated each year within the state (Title 38, §2132, n.d.).	Maine LD1467, passed in 2022, require that starting January 2026, manufacturers of plastic beverage containers should ensure that containers sold in the state have at least 25% PCR content; and 30% by January 2031 (ME LD1467, 2022).	Maine LD2091, passed in 2024, allows consumers to supply their own containers to purchase food, beverage, and non-food items. It also allows business owners to sell their products in returnable, reusable, or refillable containers/ packaging (ME LD2091, 2024).	Maine LD1541, passed in July 2, 2021, establishes a stewardship program in the state, where producers are expected to pay fees that are intended to incentivize recyclability of packaging material, use of recycled content, reduction in amount of packaging material, and lower toxicity (ME LD1541, 2021).	
US / New Jersey	New Jersey Senate Bill 864, passed in 2020, prohibits the provision or sale of single-use plastic carryout bags, single-use paper carryout bags, and polystyrene foam food service products (NJ S864, 2020). New Jersey Senate Bill 1042, proposed in January 9, 2024, prohibits the sale and distribution of any food packaging that contains intentionally-added PFAS (NJ SB1042, 2024). New Jersey Senate Bill 226, also introduced in January 9, 2024, prohibits the use of shipping box greater than two times volume of product being shipped (NJ S226, 2024).	New Jersey's goal is to recycle 50% of the municipal solid waste stream and 60% of the overall waste stream by the end of 1995 (New Jersey Department of Environmental Protection, 2017).	New Jersey Senate Bill 2515, passed in 2022, requires a minimum PCR content of 15% with 5% increases every 3 years up to 50% for beverage containers; 10% for all other rigid containers with 10% increases every 3 years up to 50%; 20% for plastic carryout bags and trash bags by 2024, and 40% by 2027; and 35% for glass containers by Jan 2024 (NJ S2515, 2022). New Jersey Assembly Bill 4367, proposed in 2024, prohibits the sale or distribution of cardboard packaging with less than 75% PCR content (NJ A4367, 2024).	No specific reuse/refill mandate for packaging were identified.	No specific EPR law for packaging was identified.	Proposed New Jersey AB4367 requires producers of plastic packaging to reduce the amount, by weight, of their packaging sold annually (NJ A4367, 2024).

Table 2.1 (cont'd).

Country / State	Packaging Prohibitions	Recycling Targets	PCR Requirements	Reuse/ Refill Mandate	EPR Obligations	Other Requirements
North America						
US / Oregon	Oregon's Senate Bill 543, passed in 2023, prohibits vendors from using PS containers in sales of prepared food, selling and distribution of PS foam packaging peanuts, as well as selling and distribution of containers with PFAS (OR SB543, 2023).	Oregon sets a statewide recovery goal of 25% for plastic waste (Oregon Department of Environmental Quality, n.d.).	Oregon requires rigid plastic containers to contain 25% PCR plastic content or reused or refilled at least five times (Oregon Department of Environmental Quality, 2007). Oregon requires glass containers to contain 50% recycled content (Oregon Legislature, 2023).	Oregon requires rigid plastic containers to contain 25% PCR plastic content or reused or refilled at least five times (Oregon Department of Environmental Quality, 2007).	Oregon's Senate Bill 582, passed in 2021, creates a producer responsibility program that requires producers of packaging to join and pay annual fees into a PRO (OR SB582, 2021).	
US / Washington	Washington Senate Bill 5323, passed in 2020, prohibits use of single-use plastic/paper carryout bag or reusable bag made that does not meet PCR content requirements (WA SB5323, 2020). Washington Senate Bill 5022, passed in 2021, prohibits the sale and distribution of EPS packing peanuts and EPS containers (WA SB5022, 2021).	No specific recycling target for packaging was identified.	Washington SB5323 requires paper bags to contain 40% PCR and capable of composting as per ASTM56868. Reusable plastic bags are required to have 20% PCR content by 2022, and 40% thereafter (WA SB5323, 2020). Washington SB5022 requires plastic beverage containers to have 15% PCR by 2023, 25% by 2026, 50% by 2031; plastic containers for household cleaning and personal care 15% by 2025, 25% by 2028, and 50% by 2031 (WA SB5022, 2021).	Washington SB5323 requires reusable bags to have a minimum lifetime of 125 uses with capacity to carry a minimum of 22 pounds over a distance of 175ft (WA SB5323, 2020).	Washington Senate Bill 5154, introduced on January 8, 2024, requires producers of packaging to join a producer responsibility organization, which by June 30, 2025, will have to submit an annual payment to fund the cost of packaging waste management (WA SB5154, 2024).	

Table 2.1 (cont'd).

Country / State	Packaging Prohibitions	Recycling Targets	PCR Requirements	Reuse/ Refill Mandate	EPR Obligations	Other Requirements
North America						
Canada	(Proposed) Fresh fruits and vegetables will be required to be distributed/ sold in bulk and/or plastic-free packaging (Environment and Climate Change Canada, 2023). Ban on manufacturing, use, and import of rigid foam plastic produced through use of CFCs or HCFCs (Ozone-depleting Substances and Halocarbon Alternatives Regulations 2016/137) (United Nations Environment Programme, 2018).	(Proposed) Requires all primary food plastic packaging to be 100% recyclable by 2028 (Environment and Climate Change Canada, 2023).	Minimum recycled content mandate, but not for food contact material (Environment and Climate Change Canada, 2023).	(Proposed) Requires all primary food plastic packaging to be 100% reusable by 2028 (Environment and Climate Change Canada, 2023).	(Proposed) Federal Plastics Registry: Brands must report type and tonnage of plastic packaging sold in Canada (Government of Canada, 2023).	
South America						
Argentina	The City of Buenos Aires prohibits the use of plastic bags in supermarkets and hypermarkets (Xanthos & Walker, 2017).	The City of Buenos Aires enforced Law No. 1854/2005 which promotes product recycling and sorting of products that can be recycled (US Department of Agriculture - Foreign Agricultural Service, 2023a).	The City of Buenos Aires enforced Law No. 1854/2005 which specifies that products produced using recycled or reused inputs must be prioritized by organizations within the city (US Department of Agriculture - Foreign Agricultural Service, 2023a).	The City of Buenos Aires enforced Law No. 1854/2005 which promotes the reduction of waste and use of long-lasting or reusable products, and measures towards the gradual replacement of disposable for reusable packaging (US Department of Agriculture - Foreign Agricultural Service, 2023a).	The City of Buenos Aires enforced Law No. 1854/2005 which obligates producer, importer, distributor, agent or any person placing a product in the market to take charge of the waste management derived from his/ her products, or participate in an organized system of waste management, or contribute to a public waste management system (US Department of Agriculture - Foreign Agricultural Service, 2023a).	

Table 2.1 (cont'd).

Country / State	Packaging Prohibitions	Recycling Targets	PCR Requirements	Reuse/ Refill Mandate	EPR Obligations	Other Requirements
South America						
Brazil	Bill No. 2726/2023 was proposed in 2023, which will establish a national policy for the control of PFAS (Koll et al., 2024).	Decree No. 11.043, enacted in April 2022, establishes targets to boost recycling rates across Brazil by 14% by 2024, and 48% by 2040 (International Trade Administration, 2023). No specific recycling target for packaging was identified.	A draft decree is underway that will set recycled content requirements for plastic packaging in Brazil (Institute for Global Environmental Strategies, 2024a).	Law 12.305/2010 encourages the reuse of packaging materials; however, it does not specify detailed requirements for their reuse (Law No. 12305, 2010).	In 2015, the Brazilian government entered into a reverse logistics agreement with a coalition of packaging companies (Langhill, 2021; Rutkowski, 2021). This agreement mandates producers to invest in waste management cooperatives, establish collection points through contracts with retailers and management systems, and educate consumers on the proper ways to return packaging for recycling (Langhill, 2021). This initiative aims to gradually reduce the amount of packaging waste sent to landfills – by 22% by 2018, and by 45% by 2031 (Rutkowski, 2021).	
Chile	Law No. 21.100, passed in 2018, prohibits establishments from providing plastic shopping bags. Plastic bags for packaging food are, however, exempted from this prohibition (Ley Núm 21.100, 2018).	Law No. 20.920, passed in 2016, sets a target of 30% recycled waste (Ley Núm. 20.920, 2016; US Department of Commerce International Trade Administration, 2023).	Law No. 21.368, passed in 2021, requires 15% minimum recycled content of Chilean origin in plastic bottles by 2025, 25% by 2030, 50% by 2040, 60% by 2050, and 70% by 2060 (US Department of Agriculture - Foreign Agricultural Service, 2021).	Law No. 21.368, published in 2021, limits the distribution of non-reusable single-use food packaging trays by food establishments. The law also requires beverage retailers to make consumers aware of the importance of returnable bottles, and their obligation to offer it for sale (Lührmann, 2023).	Law No. 20.920, passed in 2016, established "polluter pays" principle, and required all waste generators to organize and finance the waste management of priority products, which includes packaging (Ley Núm. 20.920, 2016).	

Table 2.1 (cont'd).

Country / State	Packaging Prohibitions	Recycling Targets	PCR Requirements	Reuse/ Refill Mandate	EPR Obligations	Other Requirements
Europe						
France	Ban on all single-use plastic packaging for fresh fruit and vegetables by 2026 and ban on the use of PLU stickers on fresh fruits and vegetables unless home-compostable. Ban plastic containers for infant, toddler. Ban all single use plastics by 2040	100 % of SUP recycled by 2025 (AGEC law) and 90% of plastics must be collected for recycling.	The AGEC law imposes a minimum incorporation rate of recycled plastic in beverage bottles of at least 30% for all plastic bottles by 2030	Requires that 10% of all food and non-food packaging be reusable/refillable instead of recyclable by 2027.	Articles L541-1 to L541-50 of the Code de Environment, dealing with the EPR obligations and Law 2023-305 of the 24th April 2023 on the extension and fusion of all packaging producer sectors (Titre IV : Déchets (Articles L541-1 à L542-14), 2024; LOI N° 2023-305, 2023).	AGEC Law and 3R decree impose - a reduction by 20% of SUP by 2029, - 100% elimination of non-necessary SUP (secondary packaging for instance) by end of 2025.
Spain	*Royal Decree 1055/2022* requires whole fresh fruits and vegetables to be sold loose, except for fruits and vegetables that are sold in multipacks weighing 1.5kg or more, registered varieties, those produced using ecological agriculture methods, or those at risk of deterioration if sold loose (KPMG Abogados, 2023).	*Royal Decree 1055/ 2022* targets to reduce by 13% the weight of packaging waste generated with respect to that generated in 2010 by 2025; and 15% for 2030 (KPMG Abogados, 2023).	*Law 7/2022 (Plastic Tax Law)*, which took effect January 2023, stipulates that recycled plastic is exempt from taxation, provided that companies possess a certificate from an official certifying that the packaging was recycle. However, the term "recycled plastic" is not clearly defined, leaving it unclear whether packaging must be 100% recycled plastic or if a lower percentage is permissible (Ferriz, 2023).	*Royal Decree 1055/2022* requires food retail outlets with floor area exceeding 400 m2 to designate at least 20% of their sales area to products presented without primary packaging or in reusable packaging. For food outlets exceeding 300 m2, retailers are obligated to inform consumers to return reusable packaging and to dispose separately to relevant containers; promote reusable bags and optimize use of single-use bags, as well as the availability of reusable packaging in retail outlets (KPMG Abogados, 2023).	*Royal Decree 1055/2022* obligates producers to finance and organize the management of their waste through an Extended Producer Responsibility System (EPRS) (KPMG Abogados, 2023). *Law 7/2022*, which was entered into force January 2023, imposes a special tax on non-reusable plastic packaging, which amounts to 45-euro cents per kilo of non-recycled plastic (US Department of Agriculture - Foreign Agricultural Service, 2023c).	

Table 2.1 (cont'd).

Country / State	Packaging Prohibitions	Recycling Targets	PCR Requirements	Reuse/ Refill Mandate	EPR Obligations	Other Requirements
Europe						
Germany	German Ordinance on Single-Use Plastics (*Einwegkunststoffverbots-verordnung*), implementing the requirements of Directive (EU)2019/904, prohibits to-go food containers and beverage containers/ cups made from EPS (Steinhorst & Beyerl, 2021). The same ordinance also prohibits use of oxo-degradable plastics, and single-use plastic beverage containers can only be placed on the market if their plastic closures and lids remain attached to the containers during use (Blank & Gregor, 2024). The *German Packaging Act* prohibits light plastic carrier bags with wall thickness between 15 to 50 micrometers, designed and intended to be filled at point of sale (Blank & Gregor, 2024).	The recycling targets under the *German Packaging Act* are set at 90% for glass, paper, cartons, cardboard, ferrous metals, aluminum, and plastics; 80% for beverage cartons; 70% for composites; and 63% for mechanically recycled plastics (Bünemann et al., 2020).	The *German Packaging Act* requires PET beverage bottles to contain at least 25% recycled plastic by 2025, and 30% by 2030, with the latter applying to all single-use plastic bottles (Blank & Gregor, 2024; Steinhorst & Beyerl, 2021).	The *German Packaging Act* mandates that restaurants, bistros and cafes offering takeout food or drinks must provide reusable packaging at no higher cost than disposable food packaging (Blank & Gregor, 2024). Under the *German Packaging Act*, transport packaging from manufacturers and retail must also be taken back for reuse or consigned to recovery (BMUV, 2023).	Anyone who produces or distributes packaging filled with goods, including small business owners and online retailers, are obliged to pay and enter into a system participation agreement with recovery and recycling services in Germany. The companies under legal obligation are also required to register with the *Central Agency Packaging Register – ZSVR* (Stiftung Zentrale Stelle Verpackungsregister, 2023). The Single-Use Plastics Fund Act (EWKFondsG), enacted in January 2024, requires manufacturers to cover the costs of their single-use plastics collected as public waste. They must pay a levy calculated by multiplying the mass of their reported single-use plastic products by the levy rate specified in the Single-Use Plastics Ordinance (Enders et al., 2024).	

Table 2.1 (cont'd).

Country / State	Packaging Prohibitions	Recycling Targets	PCR Requirements	Reuse/ Refill Mandate	EPR Obligations	Other Requirements
			Europe			
EU-wide	The PPWR prohibits the use of several single-use packaging formats, and food packaging containing intentionally added PFAS. It also proposes new maximum allowable limits for lead, cadmium, mercury, and hexavalent chromium in packaging, and prohibits "unnecessary" packaging layers (e.g., double walls, false bottoms), and emphasizes that weight, volume, and empty space ratio for packaging be reduced to a minimum (European Parliament, 2024). Directive (EU) 2019/904 restricts the placing on the market of food containers and beverage containers made of EPS, and products made from oxo-degradable plastics (Single-Use Plastics Directive, 2019).	The PPWR requires all packaging to be recyclable, i.e., designed for recycling by January 2030 and recycled at scale by January 2035 (European Parliament, 2024). Recycling target of 65% by weight for all packaging waste generated by 31 December 2025, and 70% by 31 December 2030 (European Parliament, 2024).	The PPWR requires that contact-sensitive packaging (except beverage bottles) made from PET plastic as major component must contain 30% PCR content by January 2030, and 50% by 2040; For contact sensitive packaging made from plastic materials other than PET, 10% PCR content by January 2030, and 25% by January 2040; For single-use plastic beverage bottles, 30% PCR by January 2030, and 65% by January 2040; For other plastic packaging, 35% PCR by January 2030, and 65% by January 2040 (European Parliament, 2024).	The PPWR requires Member States to establish a register which shall serve to monitor compliance of producers of packaging. It also prohibits producers that are not registered to make available their packaging on the market (European Parliament, 2024).	The PPWR introduces a wide range of targets on reuse and refill, and requires a system for reuse of reusable packaging to be in place. It also requires companies to ensure that 20% of beverages filled into a container at the point of sale for take-away are in reusable packaging within a system for reuse or by enabling refill by January 2030, and 80% by January 2040 (European Parliament, 2024).	The PPWR imposes several label requirements to include information on material composition, harmonized label for packaging subject to DRS, and label on packaging reusability (European Parliament, 2024). It also requires sticky labels for fruit and vegetables, filter coffee pods, and lightweight carrier bags to be compostable, as well as requires packaging to be designed to minimize its weight and volume, and empty space ratio (European Parliament, 2024).

Table 2.1 (cont'd).

Country / State	Packaging Prohibitions	Recycling Targets	PCR Requirements	Reuse/ Refill Mandate	EPR Obligations	Other Requirements
			Asia			
China	In 2020, China issued the "Opinions on Further Strengthening Plastic Pollution Control", which prohibits the use of non-degradable plastic bags in shopping malls, supermarkets, pharmacies, bookstores, and food and beverage packaging and delivery services in urban areas (Institute for Global Environmental Strategies, 2024b). GB 23350-2021: "Requirements of Restricting Excessive Package-Foods and Cosmetics" restricts the market of food and cosmetic products deemed excessively packaged as per the GB 23350-2021 standard (US Department of Agriculture - Foreign Agricultural Service, 2023b).	Target: Increase the recycling rate from 34% to 70% by 2030 (Packaging Europe, 2024). No specific recycling target for packaging was identified.	"Urgent Notice on the special rectification of plastic packaging containers for food" (2006): Recycled plastic production and processing enterprises are not allowed to sell recycled plastic to food packaging container production enterprises (Xiaowei, 2023).	"Action Plan for Advancing the Green Transformation of Express Packaging" came into effect on November 23, 2023. The action plan calls for 10% of intracity deliveries to use "recyclable express packaging" (boxes that can be reused multiple times for their original purpose), and aims to expand the reuse of old cardboard boxes (Sino-German Environmental Partnership, 2024).	Current laws and regulations on producer responsibility schemes primarily focus on electrical, electronics, automotive, and battery products, etc. There is no relevant legislation addressing producer responsibility schemes for packaging.(Lichtenstein, 2023).	
India	*Plastic Waste Management Rules, 2016* requires carry bags and plastic packaging to be either in natural shade without added pigments or made using only pigments and colorings which are in conformity with Indian Standard IS 9833:1981. It also requires plastic packaging to have thickness not less than 50 microns. Under the same rules, manufacture and use of non-recyclable multilayered plastic is prohibited (Ministry of Environment and Forests, 2016). *Plastic Waste Management (Amendment) Rules, 2021* prohibits the sale and use of single-use polystyrene and expanded polystyrene plastics effective July 1, 2022 (Ministry of Environment, Forest, and Climate Change, 2021).	*Plastic Waste Management (Amendment) Rules, 2022* requires Producers, Importers, and Brand Owners (PIBOs) of rigid plastic packaging (Category I) and compostable plastic packaging (Category IV) to recycle 50% of their EPR target by 2024, 60% by 2025, 70% by 2026, and 80% by 2027.	*Plastic Waste Management (Amendment) Rules, 2022* requires Producers of Category I packaging to incorporate 30% recycled content by 2025, 40% by 2026, 50% by 2027, and 60% by 2028 and onwards. For Category II packaging, 10% recycled content is required by 2025, and 20% by 2027. For Category III packaging, 5% is required by 2025, and 10% by 2027 and onwards (Ministry of Environment, Forest, and Climate Change, 2022)	*Plastic Waste Management (Amendment) Rules, 2022* requires Brand Owners of rigid plastic packaging, with weights less than 4.9L or kg, to reuse 10% of produced packaging by 2025, 15% by 2026, 20% by 2027, and 25% by 2028 and onwards. For rigid plastic packaging, with weights more than 4.9L, brand owners are required to reuse 70% of the produced packaging by 2025, 75% by 2026, 80% by 2027, and 85% by 2028 and onwards.	*Plastic Waste Management Rules, 2016* stipulates that PIBOs are primarily responsible for the collection of packaging they introduce to the market. They are also required to register through the online portal of the Central Pollution Control Board and provide an action plan to address EPR targets. (Ministry of Environment and Forests, 2016).	Compostable plastics are exempted from the thickness requirement, but shall conform with Indian Standard: IS 17088:2008 (Ministry of Environment and Forests, 2016).

Table 2.1 (cont'd).

Country / State	Packaging Prohibitions	Recycling Targets	PCR Requirements	Reuse/ Refill Mandate	EPR Obligations	Other Requirements
			Asia			
India (cont'd)		For flexible plastic packaging (Category II) and multilayer plastic packaging (Category III), 30% of PIBOs EPR target must be recycled by 2024, 40% by 2025, 50% by 2026, and 60% by 2027 (Ministry of Environment, Forest, and Climate Change, 2022).		For food contact applications, the packaging shall comply with the regulations set by the Food Safety and Standards Authority of India (Ministry of Environment, Forest, and Climate Change, 2022).		
Japan	The *Plastic Resource Circulation Act,* enforced in 2022, mandates retailers and service providers to reduce single-use plastics use. This can be through rewarding programs for consumers who refuse single-use plastics, charging for single-use plastics, or switching to alternative materials (Ministry of the Environment, n.d.).	Japan's *Resource Circulation Strategy for Plastics,* published in 2019, specifies a reuse/recycling target of 60% for containers and packaging by 2030 (Ministry of the Environment, 2019).	Under the current law, it is not mandatory for manufacturers to use recycled plastics. News last June 27, 2024, however, indicated that the Japanese Government is in the process of revising the *Law for the Promotion of Effective Utilization of Resources,* that is expected to obligate manufacturers to utilize recycled plastics (Kyodo News, 2024). Japan's *Resource Circulation Strategy for Plastics* specifies a target of doubling the use of recycled content by 2030 (Ministry of the Environment, 2019). Baseline values were not specified.	Japan's *Resource Circulation Strategy for Plastics* specifies a target of reusable/ recyclable design for all containers and packaging by 2025 (Ministry of the Environment, 2019).	Under the *Containers and Packaging Recycling Act*, fully enforced in 2000, business operators are expected to properly recycle the packaging they produce or use for products, either through direct recycling, or by paying the recycling fee to the *Japan Containers and Packaging Recycling Association* (Hibiki, 2024). Small businesses are exempt from these recycling obligations (Japan Containers and Packaging Recycling Association, 2020).	Under the *Plastic Resource Circulation Act*, the Japanese government developed the *"Guidelines for Design for the Environment"* for manufacturers and established a mechanism to certify the products designed in accordance with the guidelines. The administration would preferentially procure such certified products (under the *Act on Promoting Green Procurement*) and provides financial support to those manufacturers (Tsuji, 2024).

Table 2.1 (cont'd).

Country / State	Packaging Prohibitions	Recycling Targets	PCR Requirements	Reuse/ Refill Mandate	EPR Obligations	Other Requirements
			Asia			
South Korea	"*The Act on the Promotion of Saving and Recycling of Resources*" mandates that disposable products, including PET bottles, plastic plates, utensils, cups, must not be provided free of charge (United Nations Environment Programme, 2018). Ban on the use of PVC and colored PET bottle for water and beverages (US Department of Agriculture - Foreign Agricultural Service, 2022). Only colorless PET bottles have been permitted on the market, and labels for PET bottles have been recommended to be used only if consumers can easily remove them (Song & Park, 2024).	Partial amendments to the "Enforcement Decree and the Rule of the Act on the Promotion of Saving and Recycling of Resources" (2019) requires packages to be evaluated, graded (*i.e.,* "best for recycling", "excellent for recycling" "normal for recycling", "difficult for recycling"), and labeled for recyclability (Song & Park, 2024; US Department of Agriculture - Foreign Agricultural Service, 2022). South Korea has a target to reduce its plastic waste by 50% and recycle 70% (Packaging Europe, 2024).	Recycled plastics could be used in food-contact sides if the recycled plastics are repolymerized through chemical recycling or complying to the "Standards for recycled synthetic resins used for manufacturing of utensils, containers, and packages" (Ministry of Food and Drug Safety, 2021). The Korean Government requires PET bottles to have a recycled content of 30% by 2030 (C. Lee et al., 2024).	When reusing food containers or packages by recollecting, they can be used only after confirming that there are no residual impurities, etc. by cleaning with water conforming to the Water Quality Standard as provided in the Drinking Water Management Act and by cleaning with cleaning materials, etc. conforming to the Hygiene Products Control Act (Ministry of Food and Drug Safety, 2021).	South Korea's EPR policy mandates all producers and importers of EPR items to collect and recycle the products/ packaging materials (paper cartons, PET bottles, plastic composite films, metal cans, glass bottles, expanded polystyrene) or pay allotted charges to the PROs (Korea Ministry of Environment, 2010). Small manufacturers and importers are exempt from recycling obligation (Korea Ministry of Environment, 2010).	*Act on the Promotion of Saving and Recycling of Resources* sets limits on the rate of packaging space and the number of package layers for food and beverage, cosmetics, detergents, groceries, quasi-drugs, clothes, electronics, and composite products.
Thailand	*Thailand's Roadmap on Plastic Waste Management* 2018-2030 sets a target of prohibiting the use of plastic bags (less than 36 microns and) and foam food container by 2022 (Ministry of Natural Resources and Environment, n.d.).	Thailand's Roadmap on Plastic Waste Management 2018-2030 sets a target to recycle 100% of plastic waste by 2027 (Ministry of Natural Resources and Environment, n.d.).	Per Notification No. 435, published by the Thai Ministry of Public Health, packaging made from recycled plastic must have its safety assessed and certified by a safety assessment agency (Ministry of Public Health, 2022). No specific recycled content requirements for packaging were found.	No specific reuse/refill mandate for packaging were found.	EPR is currently voluntary, but mandatory EPR might be soon realized with the *Sustainable Packaging Management Act* (in draft stage) (S. Lee, 2024).	

2.2 The European Union's Packaging and Packaging Waste Regulation (PPWR)

On November 30, 2022, the European Commission introduced the Packaging and Packaging Waste Regulation (PPWR) as part of the European Green Deal (an initiative to guide the EU toward a green transition and achieve climate neutrality by 2050). The PPWR repeals Directive 94/62/EU, referred to as the Packaging and Packaging Waste Directive (PPWD), and establishes essential requirements for the design and composition of packaging, alongside collection and recycling targets (European Parliament, 2024).

A key objective of the PPWR is to address the increasing fragmentation of packaging regulations across the EU. By converting the PPWD into regulation, the PPWR seeks to eliminate internal trade barriers that impede the functioning of the single market and ensure uniform rule application among all member states. The regulation further outlines comprehensive requirements for packaging throughout its life cycle, emphasizing environmental sustainability and proper labeling for market placement. Additionally, it sets minimum standards for extended producer responsibility and defines obligations for collecting, treating, and recycling packaging waste. These requirements apply to all packaging placed on the market within the European Union. A summary of these requirements is detailed in Table 2.2, and the estimated timeline for implementing these requirements is shown in Figure 2.1.

Table 2.2 PPWR Sustainability Requirements for Packaging (as of April 24, 2024).

Article No.	Requirements
Article 5: Restrictions on Substances of Concern in Packaging	The sum of the concentration levels of lead, cadmium, mercury, and hexavalent chromium present in packaging or packaging components shall not exceed 100 mg/kg by weight. Food packaging containing intentionally added per- and polyfluorinated alkyl substances (PFAS) shall not be placed on the market.
Article 6: Recyclable Packaging	All packaging shall be recyclable. To be considered recyclable: a) Packaging is designed for recycling as set out in the delegated acts adopted by the Commission. b) Packaging is effectively and efficiently collected separately. c) Packaging is sorted into defined waste streams without affecting the recyclability of other waste streams. d) Packaging is recycled so that the resulting secondary raw materials are of sufficient quality to substitute primary raw materials. e) Packaging is recyclable at scale in accordance with the methodology.

Table 2.2 (cont'd).

Article No.	Requirements
Article 7: Minimum recycled content in plastic packaging	Contact-sensitive packaging made from PET as major component (except single use beverage bottles), and contact-sensitive packaging manufactured using plastic materials other than PET as the primary component, should include a minimum of 30% recycled content and 10% recycled content recovered from post-consumer plastic waste per packaging format by January 1, 2030, respectively. By January 1, 2040, a minimum of 50% and 25% recycled content should be achieved for contact-sensitive packaging made from PET as major component (except single-use beverage bottles) and contact-sensitive packaging manufactured using plastic materials other than PET as primary component, respectively.
Article 8: Compostable Packaging	To be considered compostable, packaging material should be capable of undergoing physical, chemical, thermal, or biological decomposition such that most of finished compost ultimately decomposes into carbon dioxide, biomass, and water, and will not hinder separate collection and composting process or activity into which it is introduced. In addition, sticky labels attached to fruits and vegetables are required to be compostable in industrially controlled conditions in bio-waste facilities.
Article 9: Packaging minimization	As of January 1, 2030, each unit of packaging shall be scaled down to its minimum size as regards its weight, volume, and layers of packaging, with due account taken of the packaging's safety and functionality. a) For bulk products, which settle after being packaged, or multiple items that need to be separated from each other within the packaging for other reasons than marketing or sales, the empty space ratio shall be maximum 25%. b) Empty space ratio for grouped and transport packaging is minimized. c) 'Unnecessary' packaging layers (i.e., double walls, false bottoms, and other unnecessary layers not fulfilling a packaging function) are prohibited.
Article 10: Reusable Packaging	Packaging is considered "reusable" where: a) It has been conceived, designed, and placed on the market with the objective of being re-used or refilled. b) It has been conceived and designed to accomplish as many trips or rotations as possible in normally predictable conditions of use. c) It can be emptied or unloaded without damage to the packaging preventing its re-use. d) It is capable of being emptied, unloaded, refilled, or reloaded while ensuring compliance with hygiene requirements. e) It is capable of being reconditioned while maintaining the packaging's ability to perform its intended function. f) Packaging can be emptied, unloaded, refilled, or reloaded without risk to the integrity of the product and to the health and safety of those responsible for doing so. g) Packaging fulfills the requirements specific to recyclable packaging when it becomes waste.

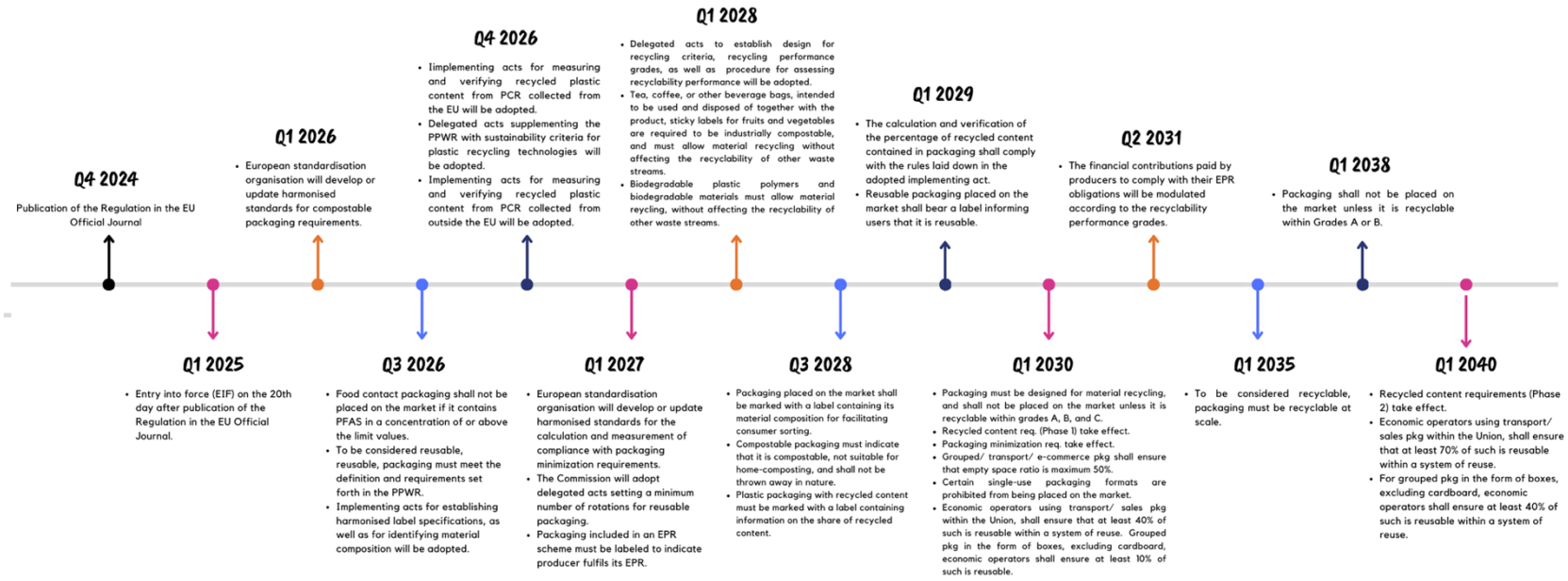


Figure 2.1 Estimated timeline of the PPWR (European Parliament, 2024).

2.3 Trade Implications of Emerging Packaging Regulations

Emerging packaging regulations are expected to significantly influence the dynamics of international trade. As these regulations evolve to enforce the inclusion of recycled content, recyclability, and/or reusability in packaging materials, industries across various sectors face the pressing challenge of adapting their operational practices to meet these new standards.

Packaging regulations increasingly act as non-tariff trade barriers, creating hurdles for companies trying to enter or expand in international markets. This is particularly impactful for the United States (U.S.), which engages in trade with over 200 countries, territories, and regional associations around the globe (United States Trade Representative (USTR), 2024; USDA Economic Research Service, 2024). The U.S. stands as the second largest agricultural trader in the world, emphasizing the importance of adhering to international standards (USDA Economic Research Service, 2024). In fiscal year 2021 alone, exports of specialty crops, which account for 14.5% of the total U.S. agricultural exports, reached an impressive $24.9 billion (United States Department of Agriculture, 2022).

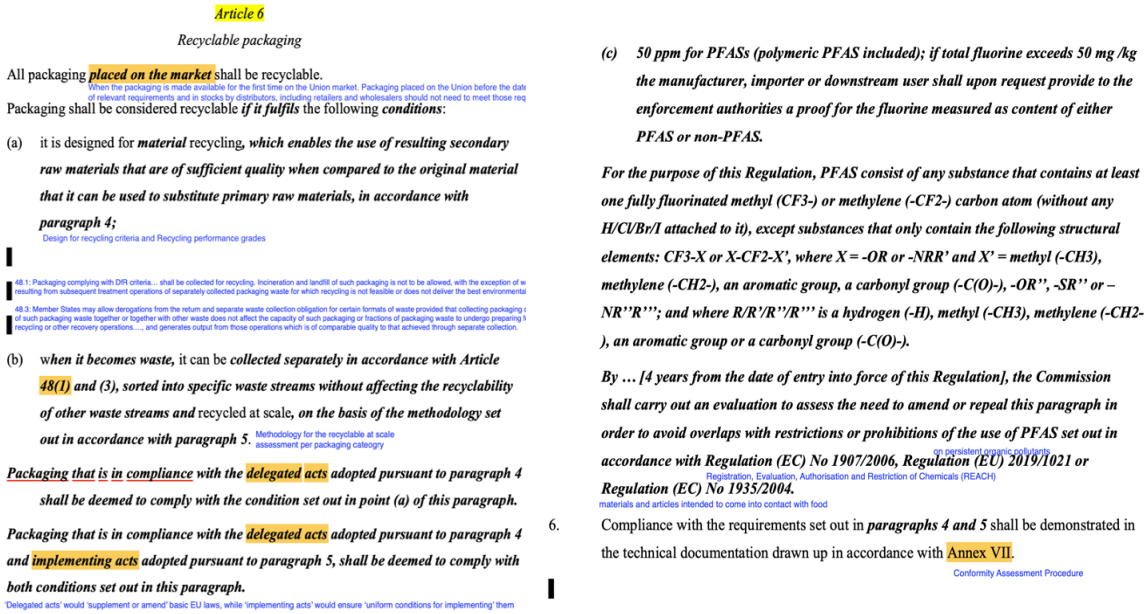
For exporters, the stakes are high. Failure to meet these emerging packaging requirements could result in severe repercussions, including border rejections of their goods. This leads to economic losses and can incur financial penalties and cause reputational damage to businesses (Johnson, 2024; United States Trade Representative (USTR), 2024). Therefore, complying with these evolving packaging regulations is not just a legal necessity; it is a critical component for successful market entry and sustainable growth in global trade.

2.4 Compliance Assessment Tool

In today's complex regulatory landscape, maintaining compliance has emerged as one of the foremost challenges organizations must navigate (Otto & Anton, 2007). These enterprises are not merely expected to stay informed about the latest legal requirements; they must also ensure that their internal policies and practices align seamlessly with these evolving standards. The stakes are high: failure to comply can lead to serious legal repercussions and hefty financial penalties. Thus, it becomes imperative for

businesses to invest in robust compliance programs proactively and to engage in continuous monitoring of regulatory changes to mitigate risks effectively.

Interpreting legal texts, however, presents considerable challenges, not only for corporations but also for individuals lacking legal expertise (Agarwal et al., 2018). Understanding these documents can often be complex and susceptible to errors, creating substantial barriers for many. Legal documents usually include specific definitions, complex cross-references, and inherent ambiguities that confuse the reader; please see Figure 2.2, for example, a sample text from the PPWR. Moreover, incomplete or unclear references can lead to inconsistent interpretations, potentially resulting in non-compliance by overlooking important exceptions and provisions. As such, ensuring compliance with regulations can be daunting for many companies, which could face hefty fines and reputation damage if not done properly.



Article 6

Recyclable packaging

All packaging ***placed on the market*** shall be recyclable.

When the packaging is made available for the first time on the Union market. Packaging placed on the Union before the date of relevant requirements and in stocks by distributors, including retailers and wholesalers should not need to meet those req

Packaging shall be considered recyclable ***if it fulfils*** the following ***conditions***:

(a) it is designed for ***material*** recycling***, which enables the use of resulting secondary raw materials that are of sufficient quality when compared to the original material that it can be used to substitute primary raw materials, in accordance with paragraph 4;***

Design for recycling criteria and Recycling performance grades

48.1: Packaging complying with DfR criteria… shall be collected for recycling. Incineration and landfill of such packaging is not to be allowed, with the exception of w resulting from subsequent treatment operations of separately collected packaging waste for which recycling is not feasible or does not deliver the best environmental

48.3: Member States may allow derogations from the return and separate waste collection obligation for certain formats of waste provided that collecting packaging of such packaging waste together or together with other waste does not affect the capacity of such packaging or fractions of packaging waste to undergo preparing f recycling or other recovery operations……, and generates output from those operations which is of comparable quality to that achieved through separate collection.

(b) w***hen it becomes waste,*** it can be ***collected separately in accordance with Article 48(1) and (3), sorted into specific waste streams without affecting the recyclability of other waste streams and*** recycled at scale***, on the basis of the methodology set out in accordance with paragraph 5.***

Methodology for the recyclable at scale assessment per packaging cateogry

Packaging that is in compliance with the delegated acts adopted pursuant to paragraph 4 shall be deemed to comply with the condition set out in point (a) of this paragraph.

Packaging that is in compliance with the delegated acts adopted pursuant to paragraph 4 and implementing acts adopted pursuant to paragraph 5, shall be deemed to comply with both conditions set out in this paragraph.

'Delegated acts' would 'supplement or amend' basic EU laws, while 'implementing acts' would ensure 'uniform conditions for implementing' them

(c) 50 ppm for PFASs (polymeric PFAS included); if total fluorine exceeds 50 mg /kg the manufacturer, importer or downstream user shall upon request provide to the enforcement authorities a proof for the fluorine measured as content of either PFAS or non-PFAS.

For the purpose of this Regulation, PFAS consist of any substance that contains at least one fully fluorinated methyl (CF3-) or methylene (-CF2-) carbon atom (without any H/Cl/Br/I attached to it), except substances that only contain the following structural elements: CF3-X or X-CF2-X', where X = -OR or -NRR' and X' = methyl (-CH3), methylene (-CH2-), an aromatic group, a carbonyl group (-C(O)-), -OR'', -SR'' or –NR''R'''; and where R/R'/R''/R''' is a hydrogen (-H), methyl (-CH3), methylene (-CH2-), an aromatic group or a carbonyl group (-C(O)-).

By … [4 years from the date of entry into force of this Regulation], the Commission shall carry out an evaluation to assess the need to amend or repeal this paragraph in order to avoid overlaps with restrictions or prohibitions of the use of PFAS set out in accordance with Regulation (EC) No 1907/2006, Regulation (EU) 2019/1021 or Regulation (EC) No 1935/2004.

on persistent organic pollutants

Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH)

materials and articles intended to come into contact with food

6. Compliance with the requirements set out in ***paragraphs 4 and 5*** shall be demonstrated in the technical documentation drawn up in accordance with Annex VII.

Conformity Assessment Procedure

Figure 2.2 Sample Text from the PPWR.

To mitigate these challenges, companies often turn to legislative compliance assessment tools. Such tools are designed to provide valuable guidance regarding their legal obligations, helping businesses ensure they remain compliant and effectively navigate the complexities of legal texts. These resources can be instrumental in reducing the likelihood of errors and fostering a better understanding of the legal landscape, ultimately safeguarding organizations against potential legal pitfalls.

Numerous compliance assessment tools available primarily focus on data protection and privacy, especially concerning data security laws like GDPR, CCPA, and HIPAA (Agarwal et al., 2018; Benedek & Bognar, 2024; Smith & Mitchell, 2020). In contrast, the packaging industry's tools designed for legislative compliance are still relatively underdeveloped. As strict packaging regulations arise, such as the EU's PPWR, the forthcoming UNEP legally binding agreement on plastic waste management, and an increasing emphasis on circular economy-driven packaging laws, there is a critical demand for compliance assessment tools explicitly focused on packaging.

2.5 Polypropylene and Its Recycling Process

Polypropylene (PP) is a thermoplastic produced by the addition polymerization of propylene (Selke & Cutler, 2013). The average molecular weight of PP ranges from 200,000 to 600,000 Daltons. It features low density (0.89–0.92 g/cm^3) and shows considerable resistance to chemicals, mechanical fatigue, and environmental stress cracking. Compared to PE, isotactic PP is notably more vulnerable to oxidative degradation from heat and light, mainly due to the presence of tertiary carbons. This oxidative degradation can lead to chain scission, which decreases molecular weight and increases the flow rate (Selke & Cutler, 2013). PP is capable of numerous commercial applications, and the demand has been consistently high (Hyie et al., 2019). Figure 2.3 illustrates the global production of plastics by polymer in 2022 (Plastics Europe, 2023). Approximately 90% of the total demand is fulfilled by five primary commodity plastics: PP, LD/LLDPE, PVC, HD/MDPE, and PET. Among these, polypropylene (PP) was the most produced polymer, making up 18.9% of the total global production.

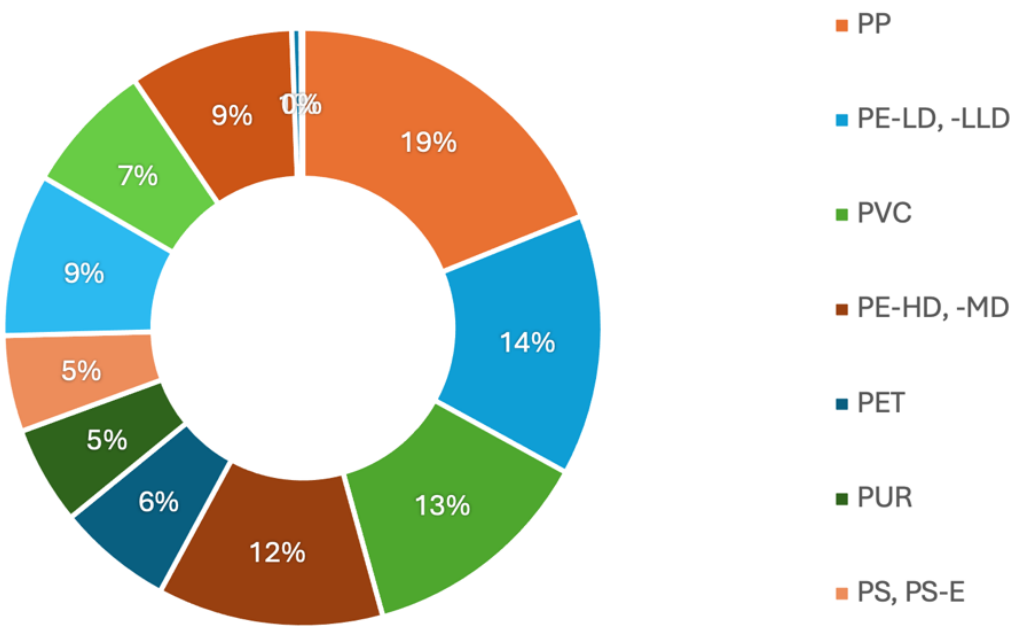


Figure 2.3 Global Plastics Production by Polymer (adapted from: Plastics Europe, 2023).

Injection molding is a key manufacturing method for polypropylene components, recognized for its versatility, efficiency, and capacity to produce complex shapes with high precision (Farotti & Natalini, 2018). In 2021, polypropylene accounted for more than 35% of the injection-molded plastic market, making it the leading material in this sector (Furion analytics Research & Consulting LLP, 2024).

Recycling PP is essential for reducing plastic waste and conserving raw materials, yet the recycling process generally impacts the properties of PP. Repeated polypropylene recycling lowers molecular weights due to thermo-mechanical and thermo-oxidative chain scission, increasing the degree of crystallinity, resulting in higher elastic moduli and decreased elongation at break (da Costa et al., 2004; Main et al., 2023; Schyns & Shaver, 2020). The reduction in elongation at break is associated with the increased crystallinity of recycled PP and the decrease in molecular weight due to multiple processing cycles (da Costa et al., 2004). Mechanical recycling of PP also leads to reduced impact strength (Aurrekoetxea & Urrutibeascoa, n.d.).

Recycling polypropylene (PP) is becoming more crucial due to the European Union's PPWR, implementing stringent recycling goals to lessen environmental impacts. According to the PPWR, packaging materials are required to achieve increasingly rigorous recycling rates, with minimum targets of

35% recycled content by 2030 and 65% by 2040 for non-PET and non-contact sensitive packaging. These targets place considerable emphasis on improving the mechanical recycling processes of plastics such as PP to ensure compliance.

2.6 Compostable Packaging Contamination in Polymer Recycling

In recent years, the use of biopolymers has increased, with global production reaching 1.8 million metric tons in 2022 (Dawoud & Taha, 2024). Given the rising consumer demand for biodegradable plastics and the increasing focus on biotechnology, it is plausible to expect an upsurge in their use in everyday applications in the coming years (The White House Office of Science and Technology Policy, 2023). However, consumers often lack adequate information on properly disposing of compostable packaging, risking contamination with petroleum-based polymer waste (Garcia-Garcia et al., 2022).

While degradation reactions during extrusion can impair recyclate quality, insufficient polymer sorting intensifies this issue. Impurities in recycled materials result in lower quality and increased variability of the regenerated polymer (Schyns & Shaver, 2020). Despite advancements in technology, plastic waste purity usually hovers around 95% (Dawoud & Taha, 2024). As a result, compostable plastics could negatively interfere with plastic mechanical recycling efforts since they could act as contaminants for traditional recycled plastics in industrial recycling lines (Garcia-Garcia et al., 2022). The impact of some biodegradable plastic polymers, such as polyhydroxyalkanoates (PHAs), on mechanical recycling processes is not yet thoroughly understood or documented (Alaerts et al., 2018; Dawoud & Taha, 2024; Kumar et al., 2023). This knowledge gap can impede effective recycling and sorting processes, potentially compromising the properties of recycled plastics.

2.7 Polyhydroxybutyrate (PHB)

Poly(3-hydroxybutyrate) (PHB), one of the most researched and commonly used types of PHAs, has attracted considerable interest in the packaging sector due to its renewable origin from organic waste and non-food crops, its biodegradability in different natural settings, its excellent oxygen, moisture, and UV barrier properties, and its mechanical characteristics that closely resemble those of traditional petrochemical plastics (Dhaini et al., 2024; Garcia-Garcia et al., 2022; Gonzales-Rojo et al., 2024).

The remarkable characteristics of PHB expand its possibilities for use as a sustainable packaging material, and it could even potentially substitute or replace conventional polymers like PP or PET in the future. In terms of molar mass, crystallinity, melting point, and tensile strength, PHB is similar to PP (Main et al., 2023). It is plausible that PHA materials, owing to their analogous properties to conventional polypropylene packaging, could inadvertently enter waste streams and contaminate recycling streams of polypropylene, thereby presenting challenges to the efficacy of recycling practices.

CHAPTER 3: METHODOLOGY

This methodology section describes the approaches taken to fulfill the research objectives of this thesis, concentrating on two distinct yet interconnected studies. Study 1 entails the development of a Compliance Assessment Tool (CAT), designed to evaluate the prospective risks and threats associated with the export of major U.S. specialty crops to the E.U., particularly in light of the recently ratified Packaging and Packaging Waste Regulation (PPWR). Study 2 investigates the potential impact of poly(3-hydroxybutyrate) (PHB) on the mechanical recycling of polypropylene (PP) in response to the new biodegradable plastics requirements under the PPWR.

3.1 Study 1: Identification of Packaging Barriers to Exporting Specialty Crops to the EU

The research methodology for Study 1 included a series of essential steps highlighted in Figure 3.1.

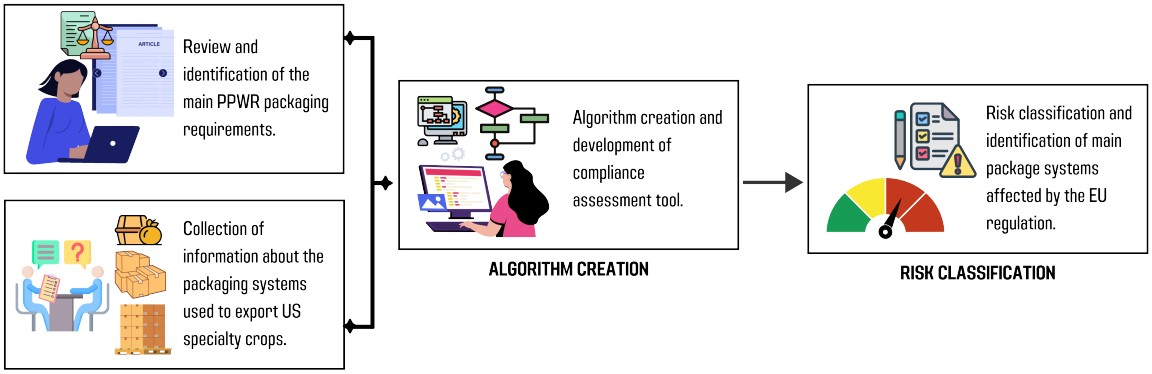


Figure 3.1 Schematic Representation of the Research Methodology.

3.1.1 In-depth review and identification of main packaging requirements

Initially, an in-depth review was carried out to identify the main packaging requirements essential for the construction of the compliance assessment tool. The tool was primarily modelled based on the sustainability requirements for packaging outlined in the European Union's PPWR, but the protocols (i.e., Packaging and Packaging Waste Directive) and standards (shown in Table 3) preceding the PPWR were also reviewed. After reviewing the main packaging requirements, several communication materials (e.g., video presentation, and flyers about the project (Appendix A), and the survey form (Appendix B) were developed, and these were provided to the identified specialty crop exporters.

Table 3.1 Standards covering packaging waste in the European Union.

Standard Number	Title
EN 13427:2004	Packaging – Requirements for the use of European Standards in the field of packaging and packaging waste
EN 13428:2004	Packaging – Requirements specific to manufacturing and composition – prevention by source reduction
EN 13429:2004	Packaging – Reuse
EN 13430:2004	Packaging – Requirements for packaging recoverable by material recycling
EN 13431:2004	Packaging – Requirements for packaging recoverable in the form of energy recovery, including specification of minimum inferior caloric value
EN 13432:2004	Packaging – Requirements for packaging recoverable through composting and biodegradation – Test scheme and evaluation criteria for the final acceptance of packaging

3.1.2 Collection of information about main packaging systems used to export U.S. specialty crops

With the assistance of the USDA Foreign Agricultural Service (FAS), several trade associations, and industry group leaders, U.S. exporters of specialty crops to the European Union were identified and contacted. The target specialty crops were almonds, pistachios, pecans, walnuts, hazelnuts, sweet potatoes, asparagus, onion, mushroom, grapefruit, tangerine, mango, cranberry, peppers, cherries, oranges, blueberries, strawberries, apples, and carrots.

Concurrently, the research team also applied for an Institutional Review Board (IRB) approval through Michigan State University's Office of Regulatory Affairs, in which the study (ID#: STUDY00009918) was subsequently granted an exempt status (Office of Regulatory Affairs Human Research Protection Program, personal communication, November 9, 2023). The research team then held individual meetings with these identified exporters to outline the project and explain the information they would be asked. Further, the exporters were notified that the interviews were confidential and that the insights shared would be aggregated into the report and not attributable to named exporters.

A survey (shown in Appendix A) was developed and conducted using the Qualtrics Survey platform. Initially, respondents were requested to provide their company name and the specialty crop that they export. The survey then gathered details about their packaging, starting with the sales packaging, the grouped packaging, and finally, the transport packaging. The respondents were provided with proper explanations to identify the three levels of packaging. The survey further collected information regarding the number of components in the packaging unit, the material used in each component, and the presence of

substances of concern, such as lead, cadmium, mercury, hexavalent chromium, PFAS, and Bisphenol A. Additionally, the survey inquired about the packaging's recyclability, reusability, and compostability.

To boost engagement, the research team also invited the contacted companies to attend several organized informational webinars. These sessions were designed to offer companies a thorough understanding of the upcoming PPWR, its potential impact on their exports to the European Union, and how the companies can benefit from participating in the surveys.

- "*PPWR2: Optimizing Packaging Systems' Safety for Reuse and Recycling in Compliance with the New Packaging and Packaging Waste Regulation"*: Held as a hybrid session on November 9-10, 2023, in Palaiseau, France. This event garnered 42 in-person attendees and 85 online participants. Topics included packaging regulations in the U.S. and E.U., and China, recycling standards in the U.S. and E.U., safety assessment criteria for recycled packaging in the U.S. and E.U., and discussions on packaging reuse, and responsible packaging education.

Figure 3.2 Photo from the organized PPWR symposium in France.

- *"Navigating the Packaging and Packaging Waste Regulation (PPWR): Insights for U.S. Specialty Crop Exporters"*: Conducted online via Zoom, garnered 56 online participants. The webinar provided an overview of the evolving global packaging regulations, specifically in Europe and Canada, and a detailed discussion on the specific requirements of the Packaging and Packaging Waste Regulation (PPWR), and its potential impact on U.S. exporters.

- *"Compostable, Reusable, and Recyclable Packaging Solutions for Navigating the European Union's Packaging and Packaging Waste Regulation (PPWR)"*: Conducted online via Zoom, which garnered 75 registrants composed of specialty crop growers/ exporters, packaging companies, IFPA members, and some consulting groups. This webinar dived deeper into sustainable packaging strategies that can help U.S. exporters comply with the PPWR. Experts in the reusable/recyclable/compostable packaging field were invited to speak in the webinar: (i) Tim Debus of the Reusable Packaging Association; (ii) Celmira Sousa of NatureWorks (iii) Scott Trenor of The Association of Plastics Recyclers; (iv) Andrew Stephens and Dorothy Butler of USDA-FAS; (v) Rafael Auras of Michigan State University.

Figure 3.3 Details of the 2nd conducted webinar.

Figure 3.4 Details of the 3rd conducted webinar.

3.1.3 Algorithm creation and development of the compliance assessment tool

The CAT was developed systematically, beginning with a comprehensive review of the sustainability requirements delineated in the PPWR. Given that numerous supplemental delegated acts and implementing acts are currently under development following the approval of the PPWR and have yet to be published, we also utilized the existing Harmonized European Committee for Standardization (CEN) standards (as outlined in Table 3.1) as a reference for devising the assessment procedure when the PPWR requirements and compliance procedures were unclear. Initial survey data from US specialty crop exporters were used to model the CAT.

The CAT, was designed as a Microsoft Excel Workbook, organized into a series of worksheets programmed to evaluate potential non-compliance of the packaging with the specific articles of the PPWR (Table 2). Excel functions and commands were strategically used to process and transform raw data into clear compliance categorizations. The SUMMARY worksheet consolidates the results from all preceding sheets, providing an overall risk assessment. Defined risk thresholds were used to assign risk levels: three or more non-compliances signify a high-risk level, one to two non-compliances indicate medium risk, and no non-compliances represent a low risk. The risk level thresholds are detailed in Table 3.2.

Table 3.2 Risk Level Thresholds.

Risk Level	Numerical Rating	Definition
Low Risk	If non-compliances equal to zero	This level suggests minimal risk since there are no instances of non-compliance. It also implies that making any needed changes to the packaging to meet requirements would likely be straightforward or minimal work.
Medium Risk	If non-compliances equal to $1 \leq \text{sum} \leq 2$	This level indicates moderate risk due to a few areas where the packaging might not fully meet sustainability requirements. Modifying the packaging in these cases could be somewhat more challenging and requiring time than in low-risk scenarios.
High Risk	If non-compliances equal to $\text{sum} \geq 3$	This level highlights substantial concerns as the packaging materials do not comply with sustainability requirements, posing significant risks. Modifying packaging in high-risk situations would likely be the most challenging, requiring extensive redesign or overhaul.

Conditional formatting was also applied with a color code for the risk assessment results: green for low risk, yellow for medium risk, and red for high risk. The color coding provides a quick visual

representation of the risk level, making it easy for users to identify potential issues with the packaging materials.

3.1.4 Risk classification and identification of main package systems affected by the PPWR

Following the algorithm creation, a risk assessment on the packaging systems of the U.S. exporters of specialty crop was conducted to determine the level of compliance and possible risks associated with the non-compliance . Areas where the existing packaging systems may fall short of EU regulatory requirements were identified. Based on these findings, recommendations were developed and communicated to the companies through a report (Sample in Appendix C).

3.2 Study 2: Assessing the Impact of PHB on the Mechanical Recycling of PP

In assessing PHB's impact on PP's mechanical recycling, recyclability evaluation protocols developed by RecyClass® and COTREP were consulted (COTREP, 2024; RecyClass, 2024). RecyClass® is a European non-profit, cross-industry initiative dedicated to enhancing packaging recyclability (RecyClass, n.d.). The organization offers guidance and support to participants in the plastic value chain by providing packaging design guidelines, recommendations for improving recyclability, an online tool for assessing recyclability, and legal recyclability certifications. COTREP, on the other hand, is a technical committee for recycling plastic packaging in France (COTREP, 2024). It publishes protocols for testing the recyclability of plastic packaging, as well as technical evaluations and guidelines for eco-design. COTREP's protocols are representative of industrial practices applied by European regeneration plants.

Study 2 was carried out in two phases (see Figure 3.4). The first phase, referred to as the Regeneration Phase, assessed the ability to transform packaging waste into useable recycled plastic pellets. The second phase focused on analyzing the generated recycled pellets for their potential to be converted into new products. Two sample batches were prepared for the lab-simulated recycling process: Sample 1 – Recycled PP (RPP) and Sample 2 – Recycled PP contaminated with 5% PHB (RPP+PHB). The

concentration of PHB was explicitly chosen to reflect the peak levels of contaminant that may be present in bales of PP due to mis-sorting or conta.mination during waste treatment.

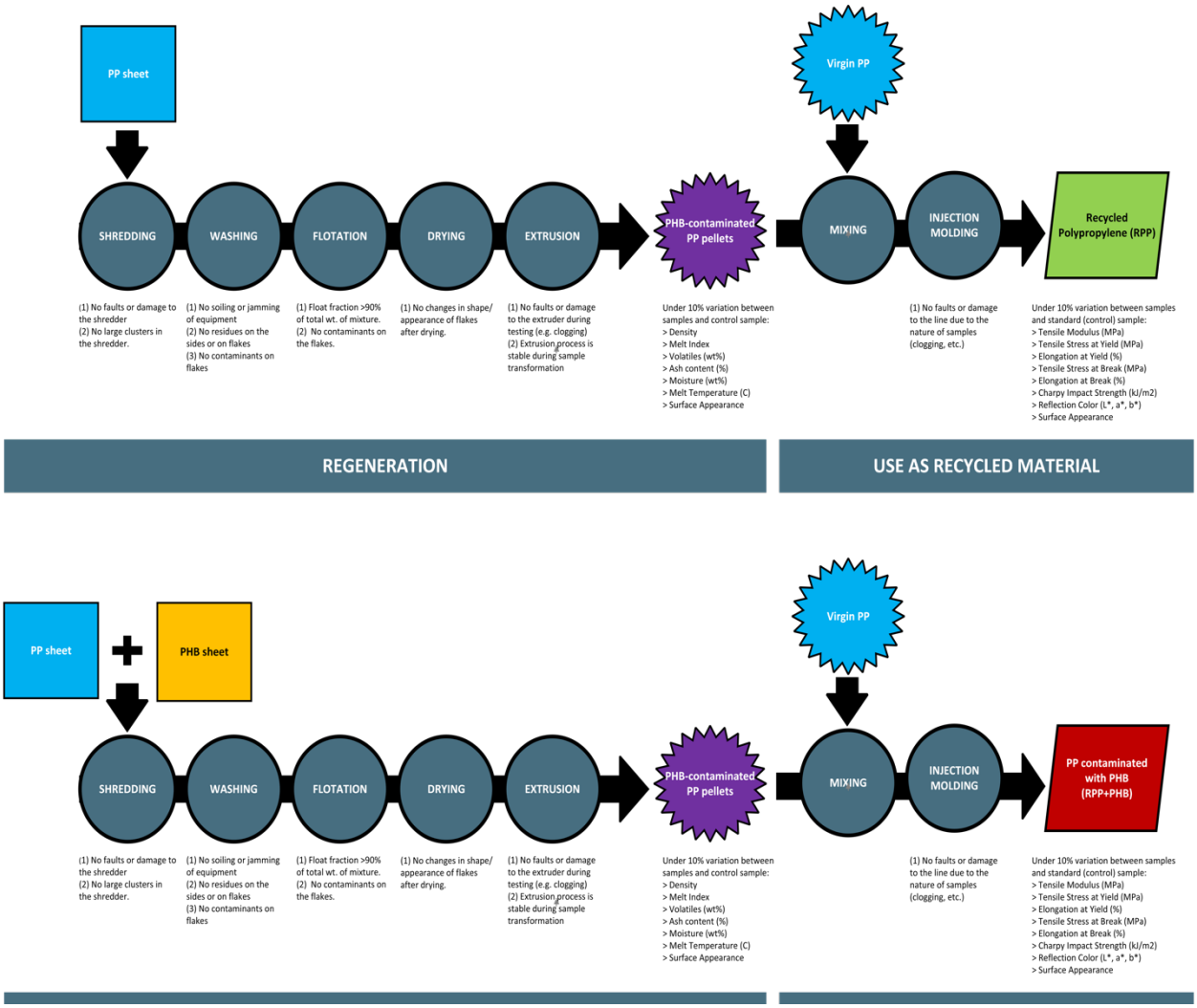


Figure 3.5 Laboratory-simulated mechanical recycling procedure for a) virgin polypropylene (RPP) and b) PP contaminated with PHB (RPP+PHB).

3.2.1 Materials

Polypropylene (PP) was obtained from ExxonMobil™ under the trade name PP6272NE1, provided as natural white pellets, with a reported density of 0.900 g/cm^3, a melt flow index (MFI) of 2.8 g/10 min, and a melting point of 140 to 170°C. Poly(hydroxybutyrate) (PHB) was obtained from Helian Polymers under the trade name ENMAT Y3000P, provided as light-brown pellets, with a reported density of 1.250 g/cm^3, an MFI of 8-15 g/10 min, and a Melting Point of 175-180°C. The resins were used as received.

3.2.2 PP and PHB Sheet Processing

PP and PHB were processed separately to produce respective sheets. The resins were extruded with a microextruder (Randcastle Extrusion Systems, Cedar Grove, NJ, USA) and made into a monolayer sheet. The extruder has a 1.5875 cm diameter screw, 34 cm^3 volume, and a 24/1 L/D ratio. The processing temperature and the extrusion conditions are provided in Table 3.3.

Table 3.3 Extrusion Parameters for Processing.

Processing Temperatures	**Temperature (°C)**
Zone 1	215
Zone 2	227
Zone 3	238
Transfer tube	238
Adapter	238
Feed block	238
Chill Roll	24
Extrusion Settings	**Speed (RPM)**
Screw	35
Chill roll speed	10

3.2.3 Shredding

The produced sheets were shredded using a plastic granulator (Polymer Machinery BTP Granulator, Michigan, USA) to produce flakes suitable for further processing. After shredding, the flakes were further sieved to produce 3mm to 15 mm-sized flakes (RecyClass, 2024).

3.2.4 Washing, Flotation, and Drying

RPP and RPP + PHB flakes were washed in a vessel at 1:4 ratio with tap water + 0.3% surfactant and 1% caustic soda (NaOH) and stirred with an overhead stirrer at 1000 rpm for 5 minutes at 80 °C (RecyClass, 2024). After 5 minutes, the solution was immediately strained, and the flakes were rinsed thoroughly with cold running tap water for 5 minutes using a manual stirring bar, then drained. Following washing, the washed flakes were separated by density through flotation. The washed flake samples were placed in a vessel at a 1:6 ratio with tap water, stirred at 750 rpm for 2 minutes, and rested for another 2 minutes. The materials that floated at the surface were removed with a sieve and air-dried (RecyClass, 2024).

3.2.5 Extrusion

Prior to extrusion, flake samples were dried with hot air at 90℃ for 1 hour to decrease the surface moisture below 1%. The samples were then extruded using a co-rotating Century ZSK 30 twin screw extruder (Century Extruders, Traverse City, MI) having a length-to-diameter (L/D) ratio of 42:1 and 30mm in diameter. The temperature profile of the twin screw extruder from the feed throat to the die was set at 220/230/230/230/230/230/230/230/230/226C. All the batches were processed at the mentioned temperatures at a screw speed of 119 rpm. The extrudate from the circular die was rapidly cooled in a water bath for cooling and fed into a pelletizer, with the pelletizer speed controlled to get a final pellet with a diameter of 3 mm.

3.2.6 Pellet Properties Characterization

The characteristics of the produced pellets were analyzed to determine their suitability for subsequent processing and use. Necessary measurements taken included density, melt index, ash content, moisture content (wt%), melt temperature, and surface appearance. RPP and RPP+PHB samples were evaluated against virgin polypropylene, which acted as the control.

3.2.6.1 Density

Density was determined following ASTM D1505-18 using an auto-density gradient column (Ray Ran, USA) with a 200F refrigerated/heating circulator (Julabo, USA) to control the water temperature (ASTM International, 2018a). A solution of isopropanol and diethylene glycol with a density range of 0.79 g/cc to 1.11 g/cc at 23°C was used and filled in the column using a microprocessor-controlled density gradient column filler (H&D Fitzgerald Ltd., St. Asaph, UK). The column was calibrated using five beads ranging in density from 0.83015 to 0.941 g/cc, with a certified calibration of $\pm$0.15 kg/m^3 per bead. A calibration curve was constructed with an $R^2 > 0.999$. The samples were allowed to equilibrate in the column for thirty minutes before measurements. Techni-Test software version 2.3.3.9 (Ray Ran, USA) was used to compile the density gradient column data.

3.2.6.2 Melt Flow Index

The Melt Flow Index (MFI) of each resin was measured using a Ray Ran (New Castle, DE, USA) Melt Flow Indexer MK II Digital Model 2A. MFI was evaluated at 230 °C with a 2.16 kg weight as per procedure A of the ASTM D1238-20 test standard (ASTM International, 2020). At least three samples of virgin polypropylene (VPP), RPP, and RPP+PHB were evaluated.

3.2.6.3 Ash Content (%)

Ash content of the pellet samples was determined using a Q50 thermogravimetric analyzer (TA Instruments, USA) from 100 to 750℃ at 10℃/min, under 50 mL/min nitrogen gas flow. Three samples (5-10mg) of each sample were evaluated.

3.2.6.4 Melt Temperature

Thermal analysis was conducted using a Q100 differential scanning calorimeter (TA Instruments) with a refrigerated cooling system under a 70 mL/min nitrogen flow. VPP, RPP, and RPP+PHB samples weighing 5 to 10 mg were packed and sealed in a standard aluminum pan and lid. The samples were ramped from 25°C to 240°C at 10°C/min with a 1-minute isotherm between each ramp. Three replicates of each sample were tested.

3.2.7 Injection Molding

The compositions from Table 3.4 were melt processed in a micro compounder (DSM Xplore 15 cc, Netherlands) at 200℃ and 100 rpm with a two-minute residence duration. These compositions were explicitly chosen to reflect the PPWR recycled content requirements for 2030 and 2040 (European Parliament, 2024). The molten composition from the extruder was then injected into a mold of T-bone and impact bar to create samples for tensile testing and Izod impact testing according to ASTM D638 and ASTM D256-10 in a micro-injector at 30℃ mold temperature and vacuum pressure of 0.8 MPa for 10 seconds (ASTM International, 2018b, 2022).

Table 3.4 Composition of injection molded samples.

Sample	VPP (g)	RPP (g)	RPP+PHB (g)
VPP (Control)	12	0	0
VPP with 35% RPP	7.8	4.2	0
VPP with 65% RPP	4.2	7.8	0
VPP with 35% RPP+PHB	7.8	0	4.2
VPP with 65% RPP+PHB	4.2	0	7.8

3.2.8 Injection Molded Parts Properties Characterization

3.2.8.1 Tensile Testing

Tensile testing was conducted on a Universal Testing System Model #5565 (Instron, USA) and measured according to ASTM D638-22 (Type V) for rigid plastic specimens. The initial strain rate was set at 1mm/min, with testing speed at 10mm/min. All samples were conditioned at 23°C and 50% RH for over 40 hours prior to testing. Bluehill version 4.25 software (Instron) is integrated with the Universal Testing System to record and calculate the data. At least six replicates of each sample were evaluated.

3.2.8.2 Izod Impact Testing

Five specimens each were created for the five different compositions. Each specimen was kept for 48 hours at standard laboratory conditions of 23°C and 50% relative humidity for conditioning after being processed in the injection molding process. A Ray-Ray impact test was used to measure the Izod impact for the specimens. The parameter for the hammer impact energy was 5.417 J, testing according to ASTM D256 standards for notched samples. The notching was done using the notch-cutting tool TMI 22-05 (Michigan, USA). The specimen was placed vertically between the grips in the Ray-Ray impact tester. The specimen was then struck with a single swing of the hammer pendulum, and the energy absorbed by the specimen was measured. The average of the five specimens was recorded and reported in kJ/m^2.

3.2.8.3 Reflection Color

The color of the samples was measured with a Hunter LabScan XE colorimeter (LX17582, Reston, VA, USA) calibrated using standard black and white tiles. The samples were placed in a standard sample cup, and triplicate readings were taken. The color parameter values, L^* (lightness, black = 0, white = 100), a^* (redness > 0, greenness <0), and b^* (yellowness > 0, blue < 0), of the samples were recorded.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Identification of Packaging Barriers to Exporting Specialty Crops to the European Union.

4.1.1 Developed Compliance Assessment Tool (CAT)

The PPWR Compliance Assessment Tool (PPWR CAT) has been effectively developed, as explained in the following paragraph. This tool includes features for data input, sustainability criteria evaluation, and risk assessment, all built using Excel functions and commands. These tools automate the processes of data transformation and risk assessment. The PPWR CAT Excel Workbook is intended to be a comprehensive resource for assessing an entire product-package system, covering sales, grouped, and transport packaging. As per definitions in the latest version of the PPWR, sales packaging refers to "packaging conceived so as to constitute a sales unit consisting of products and packaging to the end user at the point of sale" (European Parliament, 2024). Grouped packaging, on the other hand, is "packaging conceived so as to constitute a grouping of a certain number of sales units at the point of sale…", and transport packaging means "packaging conceived so as to facilitate the handling and transport of one or more sales units or a grouping of sales units…". It is systematically structured into specific worksheets, which will be examined more thoroughly in the upcoming sections of this document:

- Worksheet 1: Assessment Method
- Worksheet 2: Product Info
- Worksheet 3: A5-Restricted Substances
- Worksheet 4: A6-Recyclability
- Worksheet 5: A7-Recycled Content
- Worksheet 6: A8-Biobased Packaging (specific sustainability criteria for this PPWR article have yet to be established but are expected to be established three years following the regulation takes into force; thus, the evaluation process for this will not be covered here).
- Worksheet 7: A9-Compostability
- Worksheet 8: A10-Minimization

- Worksheet 9: A11-Reusability
- Worksheet 10: A12-Labeling
- Worksheet 11: Summary
- Worksheet 12: Disclaimer

The first worksheet of the PPWR CAT, illustrated in Figure 4.1, introduces the tool and provides the foundational references for the assessment procedure. Additionally, it provides definitions for the commonly used terms derived from the most recent version of the PPWR.

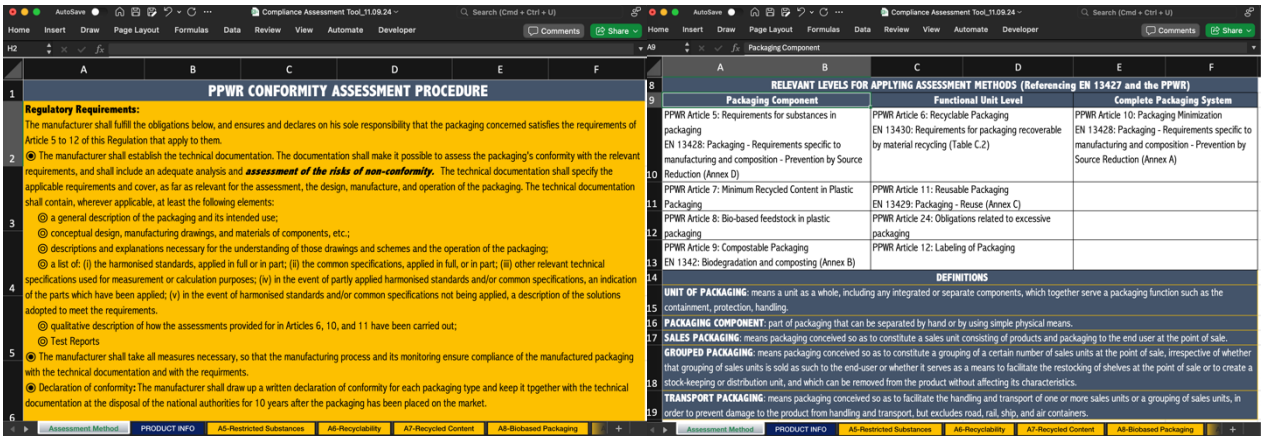
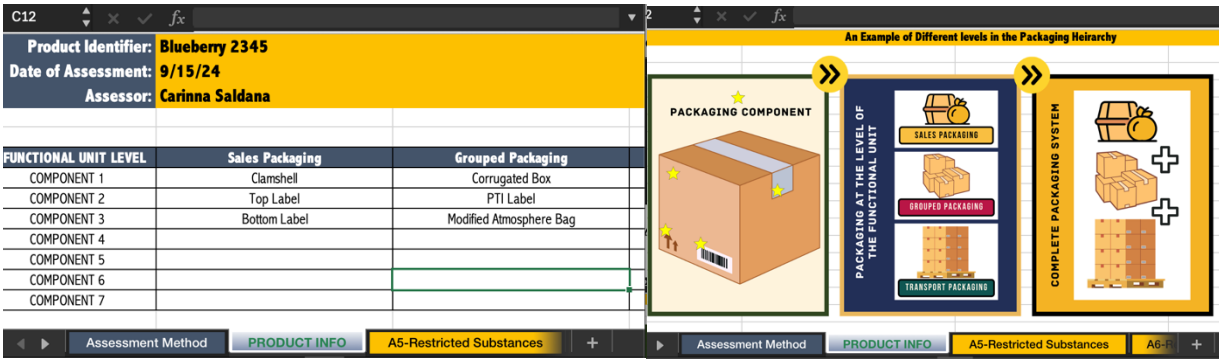


Figure 4.1 PPWR CAT Worksheet 1: Assessment Method.

The “Product Info” worksheet, illustrated in Figure 4.2, serves as the assigned worksheet for product data collection. Users specify the various components of their packaging across different functional unit levels, *i.e.,* sales packaging, grouped packaging, and transport packaging, in this worksheet. For clarity, the worksheet includes an example illustrating the distinct levels within the packaging hierarchy used in this tool, aligning with the classifications referenced in the PPWR and relevant standards.

Figure 4.3 presents the worksheet for evaluating packaging compliance with Article 5 of the PPWR: Restrictions on Substances of Concern in Packaging. This worksheet assesses whether the presence of substances of concern (e.g., lead, cadmium, mercury, hexavalent chromium) in packaging surpasses the maximum threshold of 100 mg/kg, and whether packaging, specifically food-contact packaging, adheres to per- and poly-fluoroalkyl substances (PFAS) limit requirements. The specific PPWR requirement is detailed

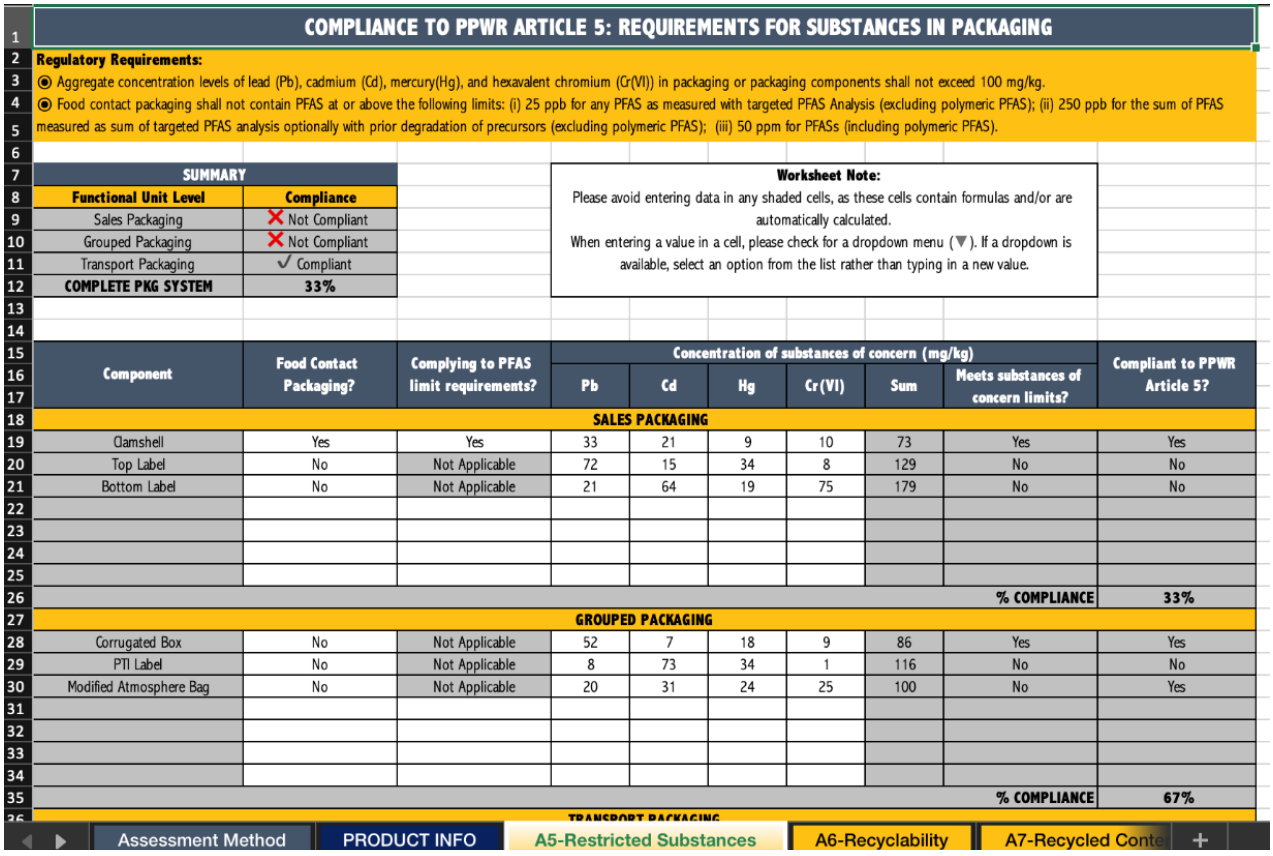
at the top portion of the worksheet for the user's reference. In this case, the limits for the substances of concern apply to all packaging components thus, the compliance evaluation will be for each component.



Product Identifier:	Blueberry 2345
Date of Assessment:	9/15/24
Assessor:	Carinna Saldana

FUNCTIONAL UNIT LEVEL	Sales Packaging	Grouped Packaging
COMPONENT 1	Clamshell	Corrugated Box
COMPONENT 2	Top Label	PTI Label
COMPONENT 3	Bottom Label	Modified Atmosphere Bag
COMPONENT 4		
COMPONENT 5		
COMPONENT 6		
COMPONENT 7		

Figure 4.2 PPWR CAT Worksheet 2: Product Info.



COMPLIANCE TO PPWR ARTICLE 5: REQUIREMENTS FOR SUBSTANCES IN PACKAGING

Regulatory Requirements:

- Aggregate concentration levels of lead (Pb), cadmium (Cd), mercury(Hg), and hexavalent chromium (Cr(VI)) in packaging or packaging components shall not exceed 100 mg/kg.
- Food contact packaging shall not contain PFAS at or above the following limits: (i) 25 ppb for any PFAS as measured with targeted PFAS Analysis (excluding polymeric PFAS); (ii) 250 ppb for the sum of PFAS measured as sum of targeted PFAS analysis optionally with prior degradation of precursors (excluding polymeric PFAS); (iii) 50 ppm for PFASs (including polymeric PFAS).

SUMMARY	
Functional Unit Level	**Compliance**
Sales Packaging	✗ Not Compliant
Grouped Packaging	✗ Not Compliant
Transport Packaging	✓ Compliant
COMPLETE PKG SYSTEM	**33%**

Worksheet Note:
Please avoid entering data in any shaded cells, as these cells contain formulas and/or are automatically calculated.
When entering a value in a cell, please check for a dropdown menu (▼). If a dropdown is available, select an option from the list rather than typing in a new value.

Component	Food Contact Packaging?	Complying to PFAS limit requirements?	Concentration of substances of concern (mg/kg)					Meets substances of concern limits?	Compliant to PPWR Article 5?
			Pb	Cd	Hg	Cr(VI)	Sum		
SALES PACKAGING									
Clamshell	Yes	Yes	33	21	9	10	73	Yes	Yes
Top Label	No	Not Applicable	72	15	34	8	129	No	No
Bottom Label	No	Not Applicable	21	64	19	75	179	No	No
								% COMPLIANCE	**33%**
GROUPED PACKAGING									
Corrugated Box	No	Not Applicable	52	7	18	9	86	Yes	Yes
PTI Label	No	Not Applicable	8	73	34	1	116	No	No
Modified Atmosphere Bag	No	Not Applicable	20	31	24	25	100	No	Yes
								% COMPLIANCE	**67%**

Figure 4.3 PPWR CAT Worksheet 3: Restricted Substances.

The user is first asked whether the specific component is categorized as “food contact packaging." Conditional formatting is implemented so that if the user responds with "No," the subsequent column cell will turn grey and display the phrase "Not Applicable." This indicates that this particular packaging

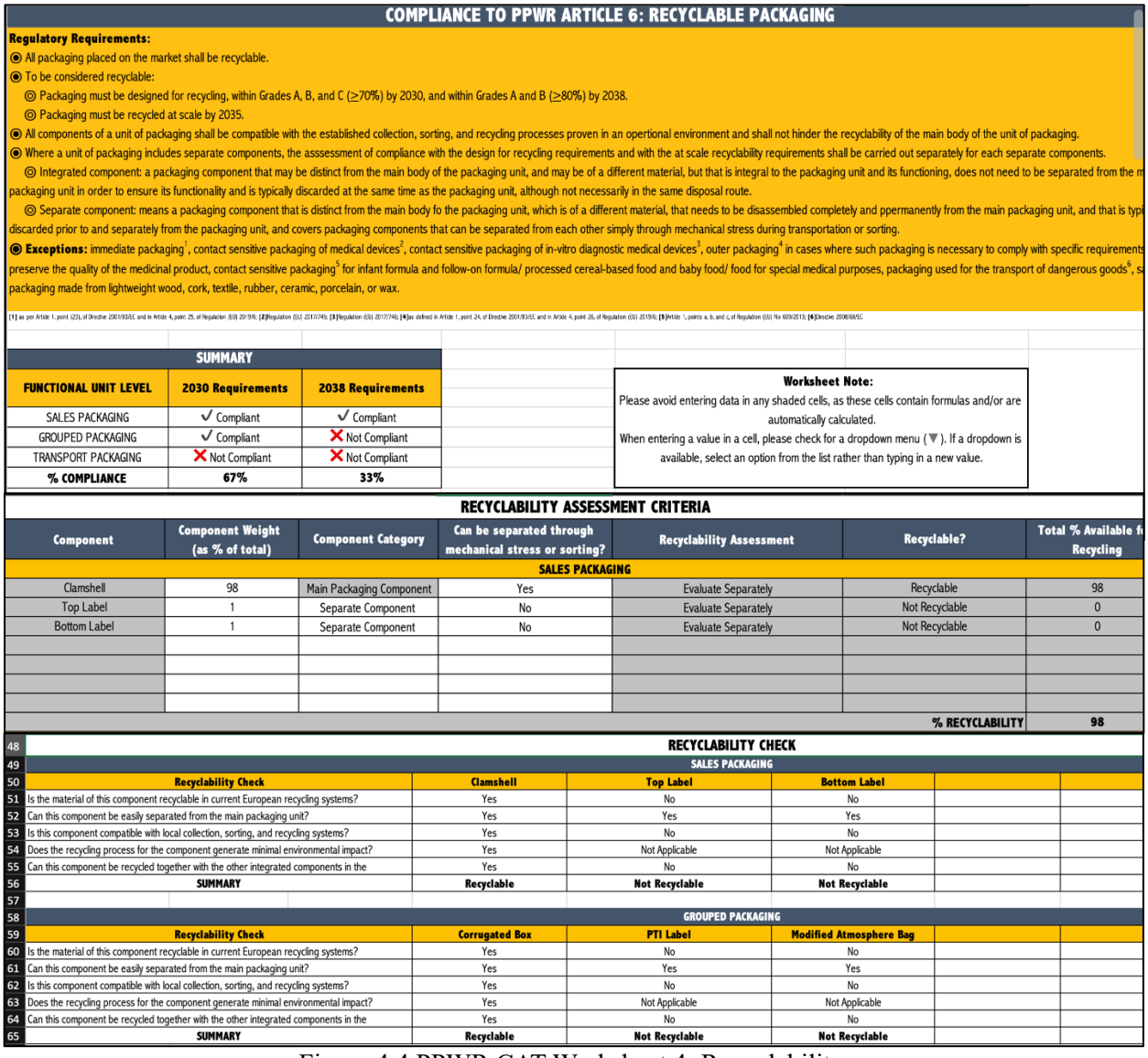
component is exempt from compliance with the PFAS requirements. Following this, the user is prompted to indicate the concentration of lead (Pb), cadmium (Cd), Mercury (Hg), and Hexavalent Chromium (Cr(VI)) in the succeeding cells per packaging component. After doing so, the “Sum” column will automatically calculate the cumulative concentration of substances of concern, and the “Meets substances of concern limits” will display “Yes” if the total is below or equal to the regulatory limit of 100mg/kg, or “No” if it exceeds this limit.

In the column titled "Compliant to PPWR Article 5?", the worksheet utilizes conditional formatting to summarize compliance regarding concerns about substance limits and PFAS limits for each component. If all requirements are fulfilled, it displays "Yes”; if not, it shows “No," highlighting the non-compliant components for further attention. The worksheet aggregates compliance information for all components at the functional unit level, presenting the compliance rate in the "% Compliance" row. Reviewing this percentage compliance per functional unit level is particularly useful, as it reflects the aggregated compliance status across all components within that unit. This is important because even if one component within a functional unit, such as Sales or Grouped Packaging, meets compliance requirements, the entire functional unit will still be marked as non-compliant if at least one component fails. When packaging is presented on the market, it is introduced as a single, unified functional unit; thus, full compliance is required across all its components for the unit to be considered compliant as a whole.

Furthermore, the total compliance percentage for the package system is shown in the upper right corner of the worksheet, giving a unified overview of its adherence to the requirements of PPWR Article 5. This metric thoroughly evaluates the packaging system’s regulatory compliance, enabling users to gauge how well the system meets the regulations swiftly, thus simplifying the identification of necessary improvements.

Figure 4.4 presents the worksheet for evaluating packaging compliance with Article 6 of the PPWR: Recyclable Packaging. For this specific PPWR Article, packaging compliance is considered at the functional-unit level (*i.e.,* sales, grouped, transport packaging). According to the existing definition of the PPWR, for a package to qualify as recyclable, it must be designed for recycling in categories A, B, and C

(≥ 70%) by 2030, and in categories A and B (≥ 80%) by 2038. As the *Design for Recycling Criteria* have not yet been released—expected from the European Standards Organisation by January 1, 2028—we have referenced the current European Standard *EN 13430: Requirements for packaging recoverable by material recycling*, for developing the assessment procedure (European Committee for Standardization, 2004). However, it's important to note that this standard is a bit outdated, as it has not been updated since 2004 (Eunomia Research & Consulting Ltd, 2020).



COMPLIANCE TO PPWR ARTICLE 6: RECYCLABLE PACKAGING

Regulatory Requirements:

- All packaging placed on the market shall be recyclable.
- To be considered recyclable:
  - Packaging must be designed for recycling, within Grades A, B, and C (≥70%) by 2030, and within Grades A and B (≥80%) by 2038.
  - Packaging must be recycled at scale by 2035.
- All components of a unit of packaging shall be compatible with the established collection, sorting, and recycling processes proven in an opertional environment and shall not hinder the recyclability of the main body of the unit of packaging.
- Where a unit of packaging includes separate components, the asssessment of compliance with the design for recycling requirements and with the at scale recyclability requirements shall be carried out separately for each separate components.
  - Integrated component: a packaging component that may be distinct from the main body of the packaging unit, and may be of a different material, but that is integral to the packaging unit and its functioning, does not need to be separated from the m packaging unit in order to ensure its functionality and is typically discarded at the same time as the packaging unit, although not necessarily in the same disposal route.
  - Separate component: means a packaging component that is distinct from the main body fo the packaging unit, which is of a different material, that needs to be disassembled completely and ppermanently from the main packaging unit, and that is typi discarded prior to and separately from the packaging unit, and covers packaging components that can be separated from each other simply through mechanical stress during transportation or sorting.
- **Exceptions:** immediate packaging[1], contact sensitive packaging of medical devices[2], contact sensitive packaging of in-vitro diagnostic medical devices[3], outer packaging[4] in cases where such packaging is necessary to comply with specific requirements preserve the quality of the medicinal product, contact sensitive packaging[5] for infant formula and follow-on formula/ processed cereal-based food and baby food/ food for special medical purposes, packaging used for the transport of dangerous goods[6], sa packaging made from lightweight wood, cork, textile, rubber, ceramic, porcelain, or wax.

[1] as per Article 1, point (23), of Directive 2001/83/EC and in Article 4, point 25, of Regulation (EU) 2017/745; [2] Regulation (EU) 2017/745; [3] Regulation (EU) 2017/746; [4] as defined in Article 1, point 24, of Directive 2001/83/EC and in Article 4, point 26, of Regulation (EU) 2017/745; [5] Article 1, points a, b, and c, of Regulation (EU) No 609/2013; [6] Directive 2008/68/EC

SUMMARY

FUNCTIONAL UNIT LEVEL	2030 Requirements	2038 Requirements
SALES PACKAGING	✓ Compliant	✓ Compliant
GROUPED PACKAGING	✓ Compliant	✗ Not Compliant
TRANSPORT PACKAGING	✗ Not Compliant	✗ Not Compliant
% COMPLIANCE	**67%**	**33%**

Worksheet Note:
Please avoid entering data in any shaded cells, as these cells contain formulas and/or are automatically calculated.
When entering a value in a cell, please check for a dropdown menu (▼). If a dropdown is available, select an option from the list rather than typing in a new value.

RECYCLABILITY ASSESSMENT CRITERIA

Component	Component Weight (as % of total)	Component Category	Can be separated through mechanical stress or sorting?	Recyclability Assessment	Recyclable?	Total % Available f Recycling
SALES PACKAGING						
Clamshell	98	Main Packaging Component	Yes	Evaluate Separately	Recyclable	98
Top Label	1	Separate Component	No	Evaluate Separately	Not Recyclable	0
Bottom Label	1	Separate Component	No	Evaluate Separately	Not Recyclable	0
					% RECYCLABILITY	**98**

RECYCLABILITY CHECK

SALES PACKAGING

Recyclability Check	Clamshell	Top Label	Bottom Label
Is the material of this component recyclable in current European recycling systems?	Yes	No	No
Can this component be easily separated from the main packaging unit?	Yes	Yes	Yes
Is this component compatible with local collection, sorting, and recycling systems?	Yes	No	No
Does the recycling process for the component generate minimal environmental impact?	Yes	Not Applicable	Not Applicable
Can this component be recycled together with the other integrated components in the	Yes	No	No
SUMMARY	**Recyclable**	**Not Recyclable**	**Not Recyclable**

GROUPED PACKAGING

Recyclability Check	Corrugated Box	PTI Label	Modified Atmosphere Bag
Is the material of this component recyclable in current European recycling systems?	Yes	No	No
Can this component be easily separated from the main packaging unit?	Yes	Yes	Yes
Is this component compatible with local collection, sorting, and recycling systems?	Yes	No	No
Does the recycling process for the component generate minimal environmental impact?	Yes	Not Applicable	Not Applicable
Can this component be recycled together with the other integrated components in the	Yes	No	No
SUMMARY	**Recyclable**	**Not Recyclable**	**Not Recyclable**

Figure 4.4 PPWR CAT Worksheet 4: Recyclability.

The assessment begins with the user assessing whether the specific packaging component can be evaluated separately or with the main packaging component. According to PPWR Article 6, “where a unit of packaging includes separate components, the assessment of compliance with the design for recycling requirements and with the at-scale recyclability requirements shall be carried out separately for each separate component.” “Separate component” as per the current version of the PPWR “means a packaging component that is distinct from the main body of the packaging unit, which is of a different material, that needs to be disassembled completely and permanently from the main packaging unit and covers packaging components that can be separated from each other simply through mechanical stress during transportation or sorting.”

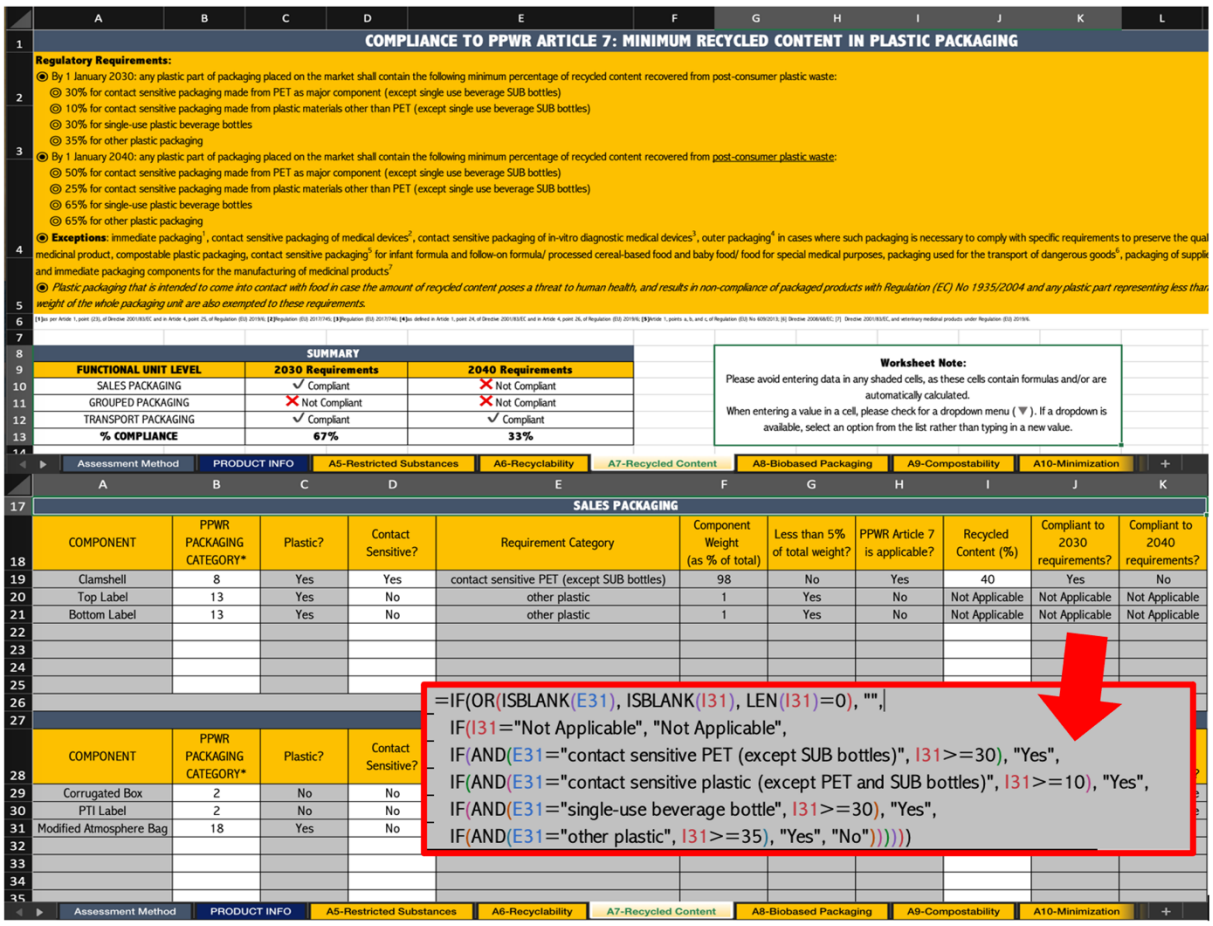
To assess whether the packaging component needs separate evaluation, users must enter the component's weight percentage in Column B relative to the total weight. Column C is conditionally formatted to identify the main packaging component by weight automatically; once identified, users can determine if the subsequent components are separate or integrated relative to the main packaging component. Additionally, the user must indicate in Column E whether this component can be separated from the main component via mechanical stress or sorting. After the user inputs all the required data, Column F automatically identifies whether the component needs to be evaluated separately or with the main packaging component.

After determining whether the packaging component should be assessed separately from the main packaging or not, they will need to complete the “Recyclability Check” section of the worksheet. This section features five questions related to the packaging component. Depending on the user’s answers (either “yes” or “no”) to these questions, the summary row will automatically determine the recyclability of the component. The worksheet then calculates the “Total % Available for Recycling," which serves as the basis for assessing whether the functional unit meets the PPWR requirements for 2030 (i.e., over 70% weight available for recycling) and the subsequent 2038 requirements (i.e., over 80% weight available for recycling). The assessment summary is shown at the top right portion of the worksheet.

Figure 4.5 displays the worksheet for assessing packaging compliance with Article 7 of the PPWR: Minimum Recycled Content in Plastic Packaging. This PPWR Article stipulates varying requirements for different types of plastic packaging, including contact-sensitive packaging made from PET (excluding single-use beverage bottles), contact-sensitive packaging from non-PET plastics (also excluding SUB bottles), single-use plastic beverage bottles, and other forms of plastic packaging. Therefore, users must first determine the type of material used in their packaging component. The PPWR includes a table that categorizes various packaging materials; this table, shown in Figure 4.6, will facilitate the assessment process.

After identifying the packaging component's category, Column C will automatically determine if the material is plastic. Users must then specify if the component is contact-sensitive, prompting Column E to indicate the applicable requirement category for the component automatically. Column F will be filled in automatically with the component weight listed in the previous worksheet, while Column G will check if it constitutes less than 5% of the total weight. Column H will determine if PPWR Article 7 is relevant to the component, which hinges on it being plastic and weighing more than 5%. If Article 7 isn't applicable, Column I will indicate “Not Applicable” for that component. However, if it is applicable, users must specify the recycled content. Subsequently, the worksheet will automatically verify compliance with the 2030 and 2040 requirements using formulas in Columns J and K, respectively. The assessment summary is shown at the top right portion of the worksheet.

Figure 4.7 illustrates the worksheet designed for evaluating packaging compliance with Article 9 of the Plastic Packaging Waste Regulation (PPWR): Compostable Packaging. This particular article of the PPWR applies exclusively to packaging components that are mandated to be compostable. For now, at least if only considering specialty crops, the PPWR only requires sticky labels affixed to fruits and vegetables to be compostable. However, the PPWR asserts that should EU Member States possess pre-existing compostable packaging requirements pertaining to other types of packaging or components before the implementation of the PPWR, those requirements shall be maintained



COMPLIANCE TO PPWR ARTICLE 7: MINIMUM RECYCLED CONTENT IN PLASTIC PACKAGING

Regulatory Requirements:

- By 1 January 2030: any plastic part of packaging placed on the market shall contain the following minimum percentage of recycled content recovered from post-consumer plastic waste:
  - 30% for contact sensitive packaging made from PET as major component (except single use beverage SUB bottles)
  - 10% for contact sensitive packaging made from plastic materials other than PET (except single use beverage SUB bottles)
  - 30% for single-use plastic beverage bottles
  - 35% for other plastic packaging
- By 1 January 2040: any plastic part of packaging placed on the market shall contain the following minimum percentage of recycled content recovered from post-consumer plastic waste:
  - 50% for contact sensitive packaging made from PET as major component (except single use beverage SUB bottles)
  - 25% for contact sensitive packaging made from plastic materials other than PET (except single use beverage SUB bottles)
  - 65% for single-use plastic beverage bottles
  - 65% for other plastic packaging
- **Exceptions**: immediate packaging[1], contact sensitive packaging of medical devices[2], contact sensitive packaging of in-vitro diagnostic medical devices[3], outer packaging[4] in cases where such packaging is necessary to comply with specific requirements to preserve the qual medicinal product, compostable plastic packaging, contact sensitive packaging[5] for infant formula and follow-on formula/ processed cereal-based food and baby food/ food for special medical purposes, packaging used for the transport of dangerous goods[6], packaging of supplie and immediate packaging components for the manufacturing of medicinal products[7]
- *Plastic packaging that is intended to come into contact with food in case the amount of recycled content poses a threat to human health, and results in non-compliance of packaged products with Regulation (EC) No 1935/2004 and any plastic part representing less than weight of the whole packaging unit are also exempted to these requirements.*

[1] as per Article 1, point (23), of Directive 2001/83/EC and in Article 4, point 25, of Regulation (EU) 2019/6; [2] Regulation (EU) 2017/745; [3] Regulation (EU) 2017/746; [4] as defined in Article 1, point 24, of Directive 2001/83/EC and in Article 4, point 26, of Regulation (EU) 2019/6; [5] Article 1, points a, b, and c, of Regulation (EU) No 609/2013; [6] Directive 2008/68/EC; [7] Directive 2001/83/EC, and veterinary medicinal products under Regulation (EU) 2019/6.

SUMMARY

FUNCTIONAL UNIT LEVEL	2030 Requirements	2040 Requirements
SALES PACKAGING	✓ Compliant	✗ Not Compliant
GROUPED PACKAGING	✗ Not Compliant	✗ Not Compliant
TRANSPORT PACKAGING	✓ Compliant	✓ Compliant
% COMPLIANCE	**67%**	**33%**

Worksheet Note:
Please avoid entering data in any shaded cells, as these cells contain formulas and/or are automatically calculated.
When entering a value in a cell, please check for a dropdown menu (▼). If a dropdown is available, select an option from the list rather than typing in a new value.

Assessment Method | PRODUCT INFO | A5-Restricted Substances | A6-Recyclability | A7-Recycled Content | A8-Biobased Packaging | A9-Compostability | A10-Minimization

SALES PACKAGING

COMPONENT	PPWR PACKAGING CATEGORY*	Plastic?	Contact Sensitive?	Requirement Category	Component Weight (as % of total)	Less than 5% of total weight?	PPWR Article 7 is applicable?	Recycled Content (%)	Compliant to 2030 requirements?	Compliant to 2040 requirements?
Clamshell	8	Yes	Yes	contact sensitive PET (except SUB bottles)	98	No	Yes	40	Yes	No
Top Label	13	Yes	No	other plastic	1	Yes	No	Not Applicable	Not Applicable	Not Applicable
Bottom Label	13	Yes	No	other plastic	1	Yes	No	Not Applicable	Not Applicable	Not Applicable

```
=IF(OR(ISBLANK(E31), ISBLANK(I31), LEN(I31)=0), "",
  IF(I31="Not Applicable", "Not Applicable",
  IF(AND(E31="contact sensitive PET (except SUB bottles)", I31>=30), "Yes",
  IF(AND(E31="contact sensitive plastic (except PET and SUB bottles)", I31>=10), "Yes",
  IF(AND(E31="single-use beverage bottle", I31>=30), "Yes",
  IF(AND(E31="other plastic", I31>=35), "Yes", "No"))))))
```

COMPONENT	PPWR PACKAGING CATEGORY*	Plastic?	Contact Sensitive?
Corrugated Box	2	No	No
PTI Label	2	No	No
Modified Atmosphere Bag	18	Yes	No

Assessment Method | PRODUCT INFO | A5-Restricted Substances | A6-Recyclability | A7-Recycled Content | A8-Biobased Packaging | A9-Compostability | A10-Minimization

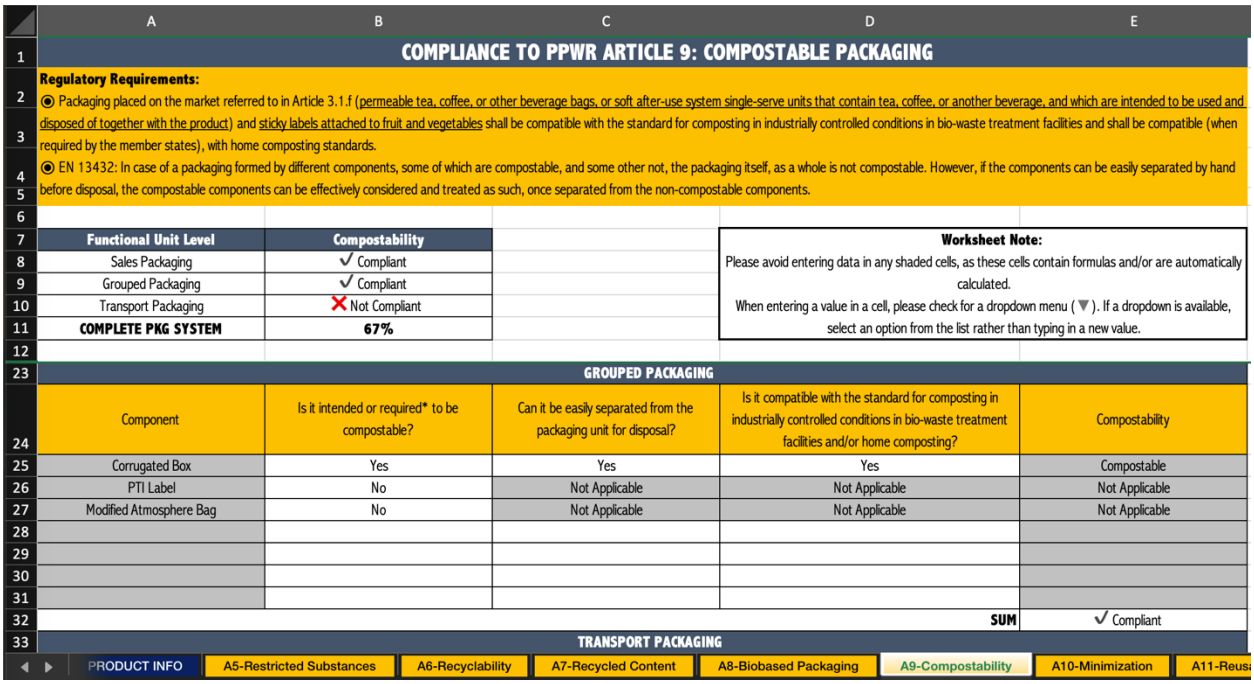
Figure 4.5 PPWR CAT Worksheet 5: Recycled Content.

FROM ANNEX II OF THE PPWR (April 24, 2024 version)

CATEGORIES AND PARAMETERS FOR ASSESSMENT OF RECYCLABILITY OF PACKAGING

CATEGORY NO.	PREDOMINANT PKG MATERIAL	PACKAGING TYPE	FORMAT (illustrative and non-exhaustive)	COLOR
1	GLASS	Glass and composite packaging, of which the majority is glass	Bottles, jars, flacons, cosmetics pots, tubs, ampoules, vials r	-
2	PAPER/CARDBOARD	Paper/cardboard packaging	Boxes, trays, grouped packaging, flexible paper packaging	-
3	PAPER/CARDBOARD	Composite packaging of which the majority is paper/ cardboard	Liquid packaging board, and paper cups (*i.e.,* laminated with	-
4	METAL	Steel and composite packaging of which the majority is steel	Rigid formats (aerosols, cans, paint tins, boxes, trays, drums	-
5	METAL	Aluminium and composite packaging of which the majority is aluminum - rigid	Rigid formats (food and beverage cans, bottles, aerosols, d	-
6	METAL	Aluminium and composite packaging of which the majority is aluminum - semi rigid and flexible	Semi rigid and flexible formats (containers and trays, tubes, f	-
7	PLASTIC	PET- rigid	Bottles and flasks	Transparent clear/ colored, opaque
8	PLASTIC	PET- rigid	Rigid formats other than bottles and flasks (includes pots, tul	Transparent clear/ colored, opaque
9	PLASTIC	PET- flexible	Films	Natural/ colored
10	PLASTIC	PE - rigid	Containers, bottles, trays, pots, and tubes	Natural/ colored
11	PLASTIC	PE - flexible	Films, including multilayer and multi-material packaging	Natural/ colored
12	PLASTIC	PP - rigid	Containers, bottles, trays, pots, and tubes	Natural/ colored
13	PLASTIC	PP - flexible	Films, including multilayer and multi-material packaging	Natural/ colored
14	PLASTIC	HDPE and PP - rigid	Crates and pallets, corrugated board plastic	Natural/ colored
15	PLASTIC	PS and XPS - rigid	Rigid formats (includes dairy packaging, trays, cups, and oth	Natural/ colored
16	PLASTIC	EPS - rigid	Rigid formats (includes fish boxes / white goods and trays)	Natural/ colored
17	PLASTIC	Other rigid plastics (e.g. PVC, PC) including multi-materials - rigid	Rigid formats, including e.g. intermediate bulk containers, dru	-
18	PLASTIC	Other flexible plastics including multi-materials - flexible	Pouches, blisters, thermoformed packaging, vacuum packag	-
19	PLASTIC	Biodegradable plastics - rigid (e.g., PLA, PHB) and flexible (e.g. PLA)	Rigid and flexible formats	-
20	WOOD, CORK	Wooden packaging, including cork	Pallets, boxes, crates	-
21	TEXTILE	Natural and synthetic textile fibers	Bags	-
22	Ceramics or porcelain s	Clay, stone	Pots, containers, bottles, jars	-

Figure 4.6 Packaging Material Categories as per the PPWR.



COMPLIANCE TO PPWR ARTICLE 9: COMPOSTABLE PACKAGING

Regulatory Requirements:

◉ Packaging placed on the market referred to in Article 3.1.f (permeable tea, coffee, or other beverage bags, or soft after-use system single-serve units that contain tea, coffee, or another beverage, and which are intended to be used and disposed of together with the product) and sticky labels attached to fruit and vegetables shall be compatible with the standard for composting in industrially controlled conditions in bio-waste treatment facilities and shall be compatible (when required by the member states), with home composting standards.

◉ EN 13432: In case of a packaging formed by different components, some of which are compostable, and some other not, the packaging itself, as a whole is not compostable. However, if the components can be easily separated by hand before disposal, the compostable components can be effectively considered and treated as such, once separated from the non-compostable components.

Functional Unit Level	Compostability
Sales Packaging	✓ Compliant
Grouped Packaging	✓ Compliant
Transport Packaging	✗ Not Compliant
COMPLETE PKG SYSTEM	**67%**

Worksheet Note:
Please avoid entering data in any shaded cells, as these cells contain formulas and/or are automatically calculated.
When entering a value in a cell, please check for a dropdown menu (▼). If a dropdown is available, select an option from the list rather than typing in a new value.

GROUPED PACKAGING

Component	Is it intended or required* to be compostable?	Can it be easily separated from the packaging unit for disposal?	Is it compatible with the standard for composting in industrially controlled conditions in bio-waste treatment facilities and/or home composting?	Compostability
Corrugated Box	Yes	Yes	Yes	Compostable
PTI Label	No	Not Applicable	Not Applicable	Not Applicable
Modified Atmosphere Bag	No	Not Applicable	Not Applicable	Not Applicable
			SUM	✓ Compliant

TRANSPORT PACKAGING

PRODUCT INFO | A5-Restricted Substances | A6-Recyclability | A7-Recycled Content | A8-Biobased Packaging | A9-Compostability | A10-Minimization | A11-Reus

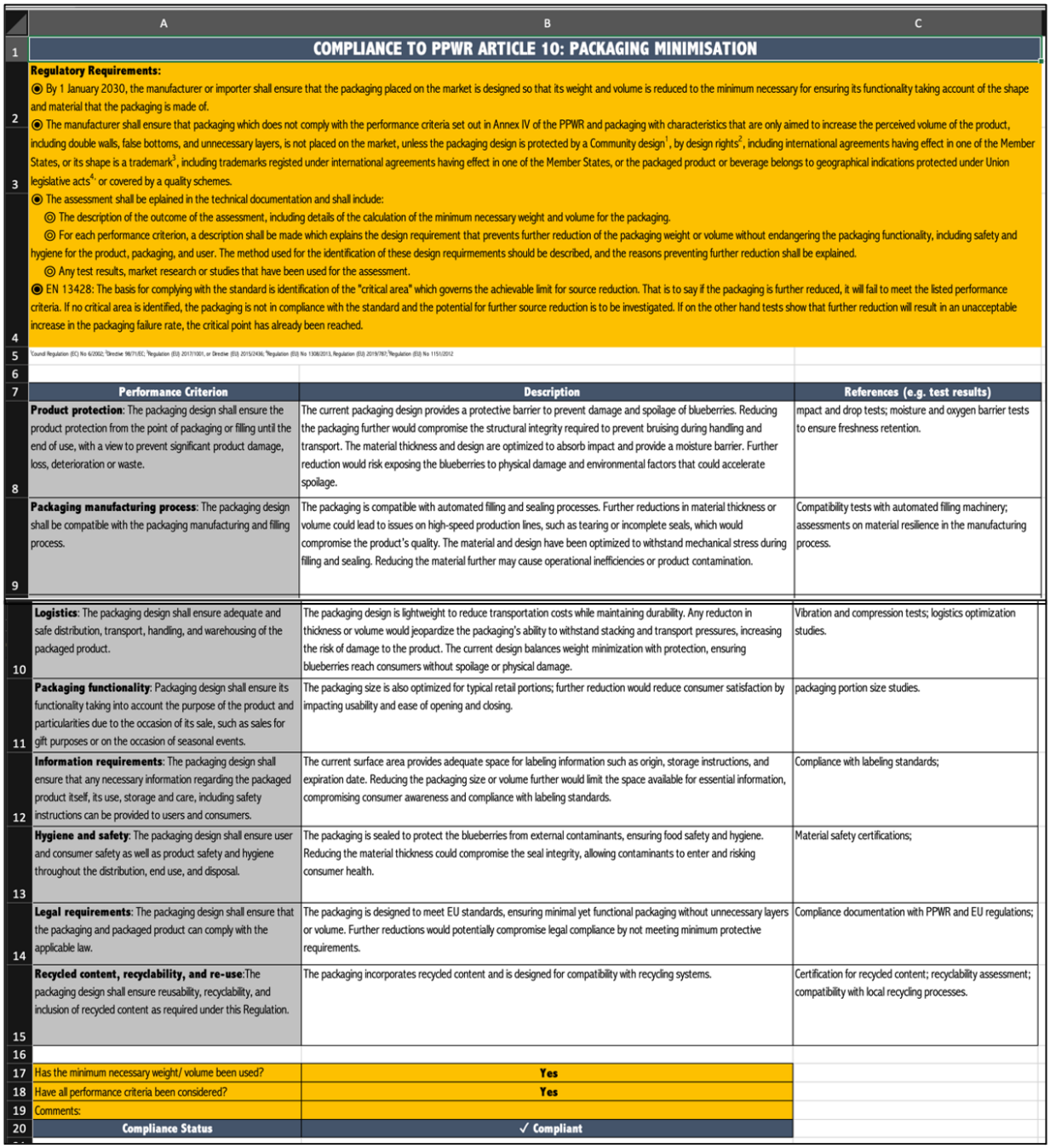
Figure 4.7 PPWR CAT Worksheet 7: Compostability.

To begin the assessment, the user must indicate in column B whether the packaging or packaging component must be compostable. If compostability is not required or intended, columns C and D will automatically show “Not Applicable." Conversely, suppose the component is intended or required to be compostable. In that case, the user will need to specify in column C whether it can be easily detached from the packaging for disposal and in Column D if it is compatible with the standard for composting in industrially controlled conditions and/or home composting. If the user answers “No” in column D, the component will not be considered compostable. Since, according to EN 13427, the assessment for compostability must be for the functional unit of packaging, the assessment for compliance with PPWR Article 9 has to be done at the functional unit level. The “Sum” row for each functional unit level will then automatically calculate if the functional unit is considered compostable or not, primarily based on whether the packaging components are compostable (when required) and easily separated from the packaging unit for disposal.

Figure 4.8 presents the worksheet used to evaluate packaging compliance with Article 10 of the Plastic Packaging Waste Regulation (PPWR): Packaging Minimization. According to PPWR Article 10,

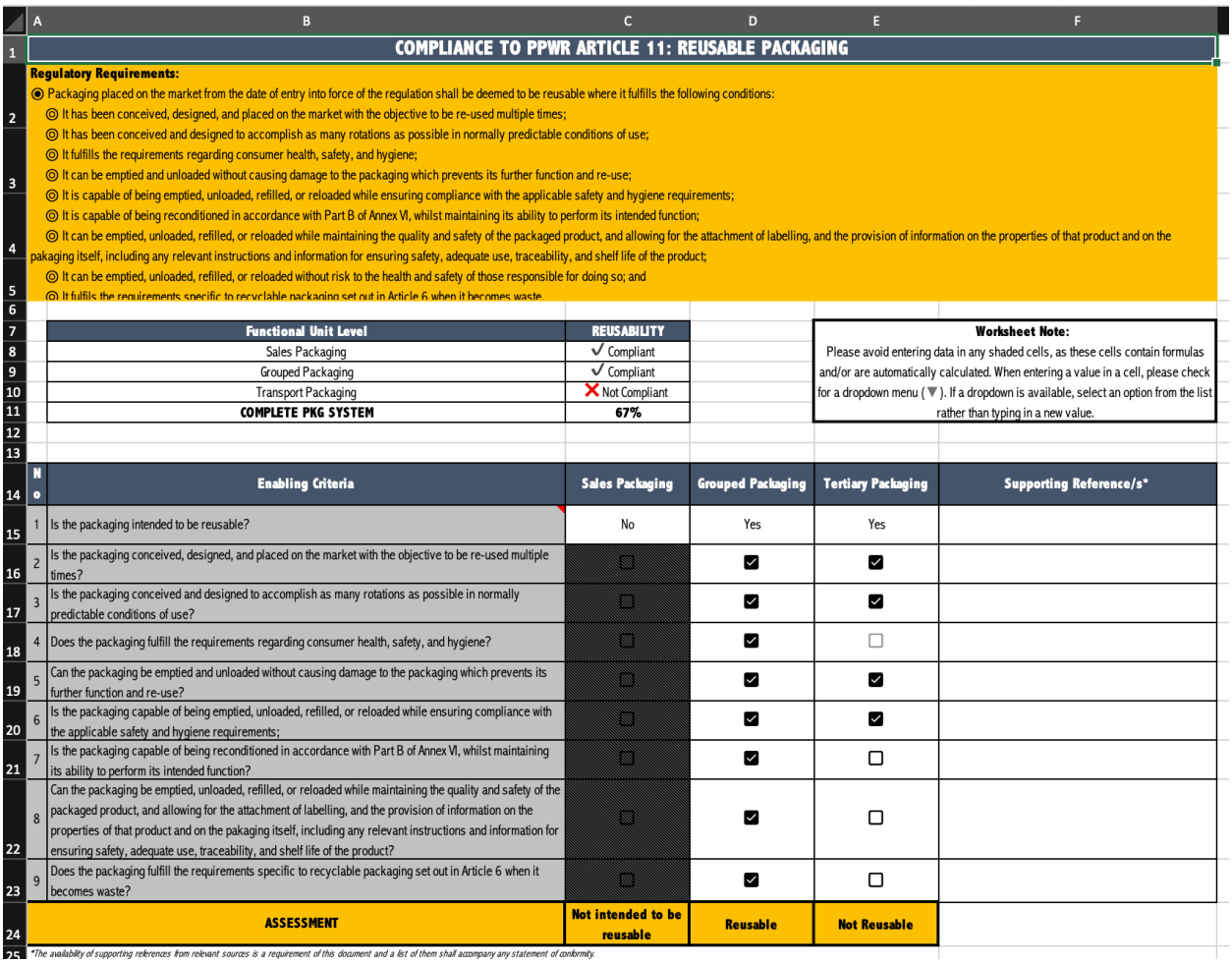
packaging must be designed to minimize its weight and volume while ensuring it remains functional. To determine compliance with this requirement, companies must assess their packaging against PPWR's outlined performance criteria (*i.e.,* product protection, packaging manufacturing process, logistics, packaging functionality, information requirements, hygiene and safety, legal requirements, recycled content, recyclability, and reuse). These criteria and their description are outlined in Column A of the worksheet. The user is required to describe their assessment in Column B, explaining how any further reductions in weight or volume might compromise the packaging's functionality based on the specified performance criteria. This assessment must include supporting references or documented evidence showing that the packaging has been optimized to the minimal extent necessary. If additional reductions could hinder performance, the company must justify these choices based on the criteria, proving that further reductions would negatively impact the packaging's functionality. Once all these conditions are met, the packaging is deemed compliant.

Figure 4.9 displays the worksheet for evaluating compliance with PPWR Article 11: Reusable Packaging. This regulation applies solely to packaging or packaging components specifically intended or claimed to be reusable. Initially, users must determine if the packaging is meant to be reusable at the functional level (e.g., sales, grouped, transport packaging). If the response is "No," subsequent questions for that packaging level are automatically shaded out, indicating that no further responses are necessary. However, if the answer is "Yes," users must respond to the following criteria by checking the checkbox for each relevant question they answer affirmatively. Once all questions are answered, the responses are totalled to indicate compliance with the requirements of PPWR Article 11. The summary of the results is shown at the top left corner of the worksheet.



	A	B	C
1	**COMPLIANCE TO PPWR ARTICLE 10: PACKAGING MINIMISATION**		
2	**Regulatory Requirements:** ◉ By 1 January 2030, the manufacturer or importer shall ensure that the packaging placed on the market is designed so that its weight and volume is reduced to the minimum necessary for ensuring its functionality taking account of the shape and material that the packaging is made of.		
3	◉ The manufacturer shall ensure that packaging which does not comply with the performance criteria set out in Annex IV of the PPWR and packaging with characteristics that are only aimed to increase the perceived volume of the product, including double walls, false bottoms, and unnecessary layers, is not placed on the market, unless the packaging design is protected by a Community design[1], by design rights[2], including international agreements having effect in one of the Member States, or its shape is a trademark[3], including trademarks registed under international agreements having effect in one of the Member States, or the packaged product or beverage belongs to geographical indications protected under Union legislative acts[4] or covered by a quality schemes.		
4	◉ The assessment shall be elained in the technical documentation and shall include: ◎ The description of the outcome of the assessment, including details of the calculation of the minimum necessary weight and volume for the packaging. ◎ For each performance criterion, a description shall be made which explains the design requirement that prevents further reduction of the packaging weight or volume without endangering the packaging functionality, including safety and hygiene for the product, packaging, and user. The method used for the identification of these design requirmements should be described, and the reasons preventing further reduction shall be explained. ◎ Any test results, market research or studies that have been used for the assessment. ◉ EN 13428: The basis for complying with the standard is identification of the "critical area" which governs the achievable limit for source reduction. That is to say if the packaging is further reduced, it will fail to meet the listed performance criteria. If no critical area is identified, the packaging is not in compliance with the standard and the potential for further source reduction is to be investigated. If on the other hand tests show that further reduction will result in an unacceptable increase in the packaging failure rate, the critical point has already been reached.		
5	[illegible]		
6			
7	**Performance Criterion**	**Description**	**References (e.g. test results)**
8	**Product protection**: The packaging design shall ensure the product protection from the point of packaging or filling until the end of use, with a view to prevent significant product damage, loss, deterioration or waste.	The current packaging design provides a protective barrier to prevent damage and spoilage of blueberries. Reducing the packaging further would compromise the structural integrity required to prevent bruising during handling and transport. The material thickness and design are optimized to absorb impact and provide a moisture barrier. Further reduction would risk exposing the blueberries to physical damage and environmental factors that could accelerate spoilage.	mpact and drop tests; moisture and oxygen barrier tests to ensure freshness retention.
9	**Packaging manufacturing process**: The packaging design shall be compatible with the packaging manufacturing and filling process.	The packaging is compatible with automated filling and sealing processes. Further reductions in material thickness or volume could lead to issues on high-speed production lines, such as tearing or incomplete seals, which would compromise the product's quality. The material and design have been optimized to withstand mechanical stress during filling and sealing. Reducing the material further may cause operational inefficiencies or product contamination.	Compatibility tests with automated filling machinery; assessments on material resilience in the manufacturing process.
10	**Logistics**: The packaging design shall ensure adequate and safe distribution, transport, handling, and warehousing of the packaged product.	The packaging design is lightweight to reduce transportation costs while maintaining durability. Any reducton in thickness or volume would jeopardize the packaging's ability to withstand stacking and transport pressures, increasing the risk of damage to the product. The current design balances weight minimization with protection, ensuring blueberries reach consumers without spoilage or physical damage.	Vibration and compression tests; logistics optimization studies.
11	**Packaging functionality**: Packaging design shall ensure its functionality taking into account the purpose of the product and particularities due to the occasion of its sale, such as sales for gift purposes or on the occasion of seasonal events.	The packaging size is also optimized for typical retail portions; further reduction would reduce consumer satisfaction by impacting usability and ease of opening and closing.	packaging portion size studies.
12	**Information requirements**: The packaging design shall ensure that any necessary information regarding the packaged product itself, its use, storage and care, including safety instructions can be provided to users and consumers.	The current surface area provides adequate space for labeling information such as origin, storage instructions, and expiration date. Reducing the packaging size or volume further would limit the space available for essential information, compromising consumer awareness and compliance with labeling standards.	Compliance with labeling standards;
13	**Hygiene and safety**: The packaging design shall ensure user and consumer safety as well as product safety and hygiene throughout the distribution, end use, and disposal.	The packaging is sealed to protect the blueberries from external contaminants, ensuring food safety and hygiene. Reducing the material thickness could compromise the seal integrity, allowing contaminants to enter and risking consumer health.	Material safety certifications;
14	**Legal requirements**: The packaging design shall ensure that the packaging and packaged product can comply with the applicable law.	The packaging is designed to meet EU standards, ensuring minimal yet functional packaging without unnecessary layers or volume. Further reductions would potentially compromise legal compliance by not meeting minimum protective requirements.	Compliance documentation with PPWR and EU regulations;
15	**Recycled content, recyclability, and re-use**:The packaging design shall ensure reusability, recyclability, and inclusion of recycled content as required under this Regulation.	The packaging incorporates recycled content and is designed for compatibility with recycling systems.	Certification for recycled content; recyclability assessment; compatibility with local recycling processes.
16			
17	Has the minimum necessary weight/ volume been used?	**Yes**	
18	Have all performance criteria been considered?	**Yes**	
19	Comments:		
20	**Compliance Status**	**✓ Compliant**	

Figure 4.8 PPWR CAT Worksheet 8: Minimization.



COMPLIANCE TO PPWR ARTICLE 11: REUSABLE PACKAGING

Regulatory Requirements:

◉ Packaging placed on the market from the date of entry into force of the regulation shall be deemed to be reusable where it fulfills the following conditions:

◎ It has been conceived, designed, and placed on the market with the objective to be re-used multiple times;

◎ It has been conceived and designed to accomplish as many rotations as possible in normally predictable conditions of use;

◎ It fulfills the requirements regarding consumer health, safety, and hygiene;

◎ It can be emptied and unloaded without causing damage to the packaging which prevents its further function and re-use;

◎ It is capable of being emptied, unloaded, refilled, or reloaded while ensuring compliance with the applicable safety and hygiene requirements;

◎ It is capable of being reconditioned in accordance with Part B of Annex VI, whilst maintaining its ability to perform its intended function;

◎ It can be emptied, unloaded, refilled, or reloaded while maintaining the quality and safety of the packaged product, and allowing for the attachment of labelling, and the provision of information on the properties of that product and on the pakaging itself, including any relevant instructions and information for ensuring safety, adequate use, traceability, and shelf life of the product;

◎ It can be emptied, unloaded, refilled, or reloaded without risk to the health and safety of those responsible for doing so; and

◎ It fulfils the requirements specific to recyclable packaging set out in Article 6 when it becomes waste

Functional Unit Level	REUSABILITY
Sales Packaging	✓ Compliant
Grouped Packaging	✓ Compliant
Transport Packaging	✗ Not Compliant
COMPLETE PKG SYSTEM	**67%**

Worksheet Note:
Please avoid entering data in any shaded cells, as these cells contain formulas and/or are automatically calculated. When entering a value in a cell, please check for a dropdown menu (▼). If a dropdown is available, select an option from the list rather than typing in a new value.

No	Enabling Criteria	Sales Packaging	Grouped Packaging	Tertiary Packaging	Supporting Reference/s*
1	Is the packaging intended to be reusable?	No	Yes	Yes	
2	Is the packaging conceived, designed, and placed on the market with the objective to be re-used multiple times?	☐	☑	☑	
3	Is the packaging conceived and designed to accomplish as many rotations as possible in normally predictable conditions of use?	☐	☑	☑	
4	Does the packaging fulfill the requirements regarding consumer health, safety, and hygiene?	☐	☑	☐	
5	Can the packaging be emptied and unloaded without causing damage to the packaging which prevents its further function and re-use?	☐	☑	☑	
6	Is the packaging capable of being emptied, unloaded, refilled, or reloaded while ensuring compliance with the applicable safety and hygiene requirements;	☐	☑	☑	
7	Is the packaging capable of being reconditioned in accordance with Part B of Annex VI, whilst maintaining its ability to perform its intended function?	☐	☑	☐	
8	Can the packaging be emptied, unloaded, refilled, or reloaded while maintaining the quality and safety of the packaged product, and allowing for the attachment of labelling, and the provision of information on the properties of that product and on the pakaging itself, including any relevant instructions and information for ensuring safety, adequate use, traceability, and shelf life of the product?	☐	☑	☐	
9	Does the packaging fulfill the requirements specific to recyclable packaging set out in Article 6 when it becomes waste?	☐	☑	☐	
	ASSESSMENT	**Not intended to be reusable**	**Reusable**	**Not Reusable**	

*The availability of supporting references from relevant sources is a requirement of this document and a list of them shall accompany any statement of conformity.

Figure 4.9 PPWR CAT Worksheet 9: Reusable.

Figure 4.10 showcases the worksheet designed for assessing packaging compliance with PPWR Article 12: Labelling of Packaging. Like Article 11, users are required to respond with "Yes" or "No" to a series of label questions listed in Column A of the worksheet. To make the questions easily understandable by the user, these questions are categorized into general label inquiries, and further classified based on whether they are reusable, compostable, or part of the EPR scheme. If users respond "No" to any general classification, the subsequent questions in that category will not be displayed. Once all questions are answered, the results appear in the "Assessment Summary" section of the worksheet

	A	B
1	**COMPLIANCE TO PPWR ARTICLE 12: LABELLING OF PACKAGING**	
2	**Regulatory Requirements:** ◉ 42 months from the date of entry into force of this regulation (est. Q3 2028), packaging placed on the market shall: ◎ be marked with a label containing information on its material composition. ◎ Where applicable, label shall indicate that the packaging material is compostable, not suitable for home-composting, and compostable packaging shall not be thrown away in nature. ◎ Packaging that is subject to deposit and return systems shall be marked with a clear and unambiguous label. ◎ Exceptions: Transport packaging (except e-commerce packaging), and packaging part of a deposit and return system.	
3	◉ 48 months from the date of entry into force of this regulation (est.) reusable packaging placed on the market shall bear a label informing users that the packaging is reusable. Information on reusability (*i.e.,* availability of a local, national, or EU-wide system for reuse and information on collection points) shall be made available through a QR code or other type of standardized, open, digital data carrier, that facilitates the tracking of the packaging and the calculation of trips and rotations. Reusable packaging shall be clearly identified and distinguished from single-use packaging at the point of sale. ◉ 42 months from the date of entry into force of the PPWR, packaging covered by Article 7 shall be marked with a label containing information on the share of recycled content. Where a packaging is marked with a label containing information on the share of bio-based plastic content, that label shall comply with the specifications laid	
6		
7	**ASSESSMENT SUMMARY**	
8	**FUNCTIONAL UNIT LEVEL**	**COMPLIANCE**
9	Primary Packaging	✗ Not Compliant
10	Secondary Packaging	✓ Compliant
11	Tertiary Packaging	✗ Not Compliant
12	**COMPLETE PKG SYSTEM**	**33%**
15	**PRIMARY PACKAGING**	
16	**Requirement**	**Compliant?**
17	Packaging label indicates material composition?	Yes
18	Label, marks, symbols, or inscriptions in packaging not misleading with respect to compliance with sustainability requirements?	Yes
19	Is information on the share of recycled content (for plastic components representing >5% by wt.) present on the label?	Yes
20	Is the packaging compostable?	Yes
21	Does the compostable packaging indicate that the material is compostable, not suitable for home composting, and that it should not be thrown away in nature?	No
22	Is the packaging reusable?	Yes
23	Does the reusable packaging have a label indicating it is reusable?	Yes
24	Does the reusable packaging feature a QR code that offers information on available local, national, or EU-wide reuse systems, nearby collection points, and tracks the tracks the packaging's journey, including the number of trips and rotations completed?	No
25	Can the reusable packaging be clearly identified and distinguished from single-use packaging at point of sale?	Yes
26	Is the packaging included in an EPR scheme?	Yes
27	Does the packaging have a clear and unambiguous symbol, QR code, or other standardized digital marking technology that provides information on which territory of the Member States the EPR scheme applies?	Yes
28		
29		
30	**SECONDARY PACKAGING**	
31	**Requirement**	**Check if Compliant**
32	Packaging label indicates material composition?	Yes
33	Label, marks, symbols, or inscriptions in packaging not misleading with respect to compliance with sustainability requirements?	Yes
34	Is information on the share of recycled content (for plastic components representing >5% by wt.) present on the label?	Yes
35	Is the packaging compostable?	No
36		
37	Is the packaging reusable?	Not Applicable
38		
39		
40		
41	Is the packaging included in an EPR scheme?	Yes
42	Does the packaging have a clear and unambiguous symbol, QR code, or other standardized digital marking technology that provides information on which territory of the Member States the EPR scheme applies?	Yes

Figure 4.10 PPWR CAT Worksheet 10: Labelling.

The Summary Worksheet (Figure 4.11) clearly visualizes how the packaging system meets the PPWR requirements, enabling users to quickly spot specific packaging units and components that do not meet the compliance targets for 2030 and 2038/ 2040. This visual breakdown emphasizes essential areas that need improvement. By identifying packaging units or components with the highest levels of non-compliance, the worksheet acts as a strategic resource for illustrating regulatory gaps and devising targeted interventions to ensure a fully compliant packaging system.

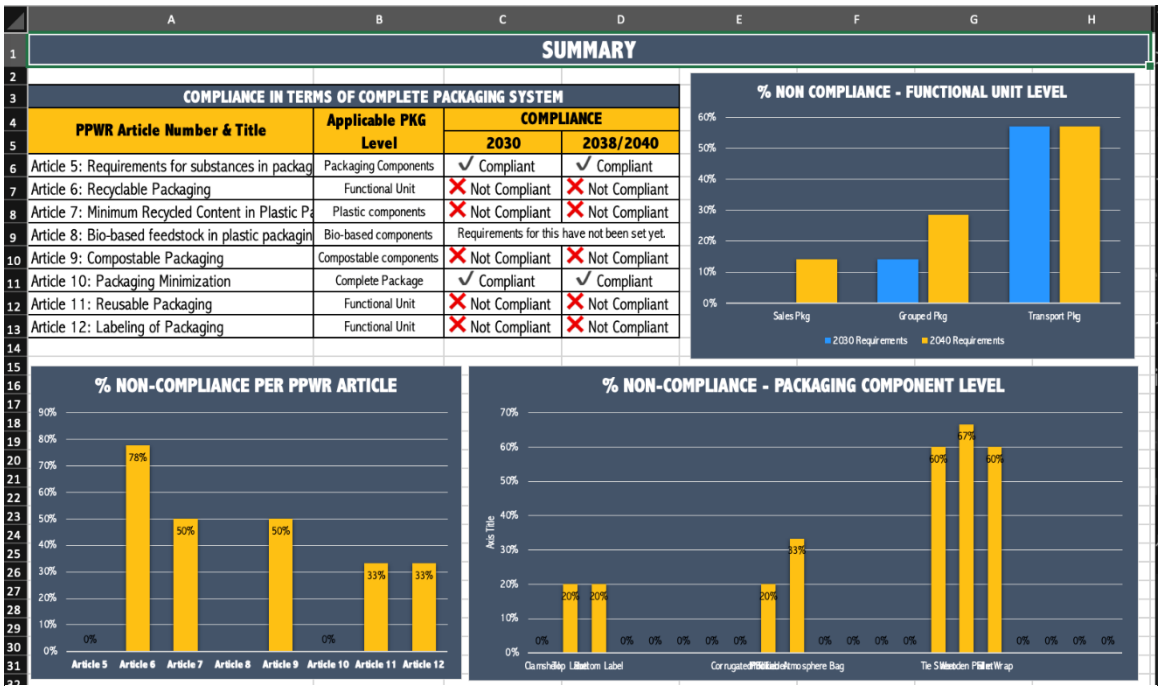


Figure 4.11 PPWR CAT Worksheet 11: SUMMARY.

The table at the top-left portion of the worksheet summarizes compliance with the PPWR articles for the overall packaging system. It shows whether the packaging meets the requirements for each PPWR article by the target years 2030 and 2038/2040. To reflect "compliant" status in terms of the overall packaging system, each packaging unit at the functional unit level (*i.e.,* sales, grouped, transport packaging) must comply with the specific PPWR Article. The top-right bar chart labeled "% Non-Compliance – Functional Unit Level" shows non-compliance rates for each functional unit (Sales Packaging, Grouped Packaging, and Transport Packaging) for the target years 2030 and 2038/2040. This lets users quickly

identify which packaging unit is particularly problematic and requires significant changes to meet the established PPWR requirements. The lower-right bar chart labeled "% Non-Compliance – Packaging Component Level," on the other hand, delves into specific packaging components showing the non-compliance percentage for each component.

In the same worksheet, below the bar charts, is a table detailing how each packaging unit complies with specific PPWR articles for the 2030 and 2040 targets. This table automatically computes and categorizes the packaging units by their non-compliance risk levels: high, medium, and low. To illustrate these risk levels visually, conditional formatting was applied with green signifying low risk, yellow for medium, and red indicating high. The risk level thresholds are detailed in Figure 4.12.

COMPLIANCE PER FUNCTIONAL UNIT LEVEL						
PPWR Article Number & Title	2030 COMPLIANCE			2038/2040 COMPLIANCE		
	SALES PKG	GROUPED PKG	TRANSPORT PKG	SALES PKG	GROUPED PKG	TRANSPORT PKG
Article 5: Requirements for substances in packaging	✓ Compliant	✓ Compliant	✓ Compliant	✓ Compliant	✓ Compliant	✓ Compliant
Article 6: Recyclable Packaging	✓ Compliant	✓ Compliant	✗ Not Compliant	✓ Compliant	✗ Not Compliant	✗ Not Compliant
Article 7: Minimum Recycled Content in Plastic Packaging	✓ Compliant	✗ Not Compliant	✓ Compliant	✗ Not Compliant	✗ Not Compliant	✓ Compliant
Article 8: Bio-based feedstock in plastic packaging	Requirements for this have not been set yet.			Requirements for this have not been set yet.		
Article 9: Compostable Packaging	✓ Compliant	✓ Compliant	✗ Not Compliant	✓ Compliant	✓ Compliant	✗ Not Compliant
Article 10: Packaging Minimization	✓ Compliant	✓ Compliant	✓ Compliant	✓ Compliant	✓ Compliant	✓ Compliant
Article 11: Reusable Packaging	✓ Compliant	✓ Compliant	✗ Not Compliant	✓ Compliant	✓ Compliant	✗ Not Compliant
Article 12: Labeling of Packaging	✓ Compliant	✓ Compliant	✗ Not Compliant	✓ Compliant	✓ Compliant	✗ Not Compliant
	Low Risk	Medium Risk	High Risk	Medium Risk	Medium Risk	High Risk

Figure 4.12 PPWR CAT Worksheet: Summary - Risk Assessment.

4.2 Risk classification and identification of main package systems affected by the PPWR.

Using the initial survey data obtained from specialty crop exporters, we evaluated the extent of compliance of these packaging systems with the PPWR. This analysis examines compliance across twenty-nine (29) packaging units at the functional level, encompassing a total of 45 packaging components. Figure 4.13 displays a summary of non-compliance percentages across different PPWR articles. It is pertinent to note that PPWR Articles 8, 10, and 12 were excluded from this analysis. The specific requirements for PPWR Article 8: Bio-based feedstock in plastic packaging have not yet been established, whereas *PPWR Article 10: Packaging Minimisation* and *PPWR Article 12: Labelling* were excluded to simplify the questionnaire and lessen the burden on the respondents.

Figure 4.13 shows that the highest non-compliance rate is associated with *PPWR Article 7: Minimum Recycled Content in Plastic Packaging*, followed by *Article 6: Recyclable Packaging*. In contrast, companies adhered fully to *PPWR Article 5: Requirements for Substances of Concern*, with no non-compliance reported. *PPWR Articles 9 and 11* apply to compostable and reusable packaging, respectively, meaning the requirement applies only when the packaging is either intended for or required by regulation to be compostable or reusable. None of the evaluated packaging units fell under these PPWR articles, thus no non-compliance was recorded.

Figure 4.14 shows the distribution of risk levels across the various packaging levels in the study. Among the three packaging systems evaluated, the transport packaging system exhibited the highest rate of non-compliance. This is likely due to the more complex nature of transport packaging, which utilizes a wider variety of materials than the other levels (illustrated in Figure 4.15). The variety of materials within the packaging unit presents significant challenges for meeting compliance standards, particularly since adherence to most PPWR articles (such as evaluation of recyclability based on outdated standards) is evaluated based on the packaging unit as a whole rather than on individual components. However, this assessment may change in the coming years once the design for recycling criteria are updated and made available.

Most of the packaging assessed was reported to be recyclable, especially for the grouped packaging level, as shown in Figure 4.17. Grouped packaging, typically comprising corrugated board or paper-based materials, is generally highly recyclable due to its more straightforward design and established recycling infrastructure (Auras & Selke, 2023; US Environmental Protection Agency, 2020). In contrast, the sales and transport packaging levels assessed were more complex, comprising more varied materials in its system, including plastics, wood, and various composites (see Figure 4.16 for example). Recycling plastic packaging, for instance, presents particular challenges as it uses a wide variety of polymers and other materials such as metals, paper, pigments, inks, and adhesives that increase the difficulty of recycling (Hopewell et al., 2009).

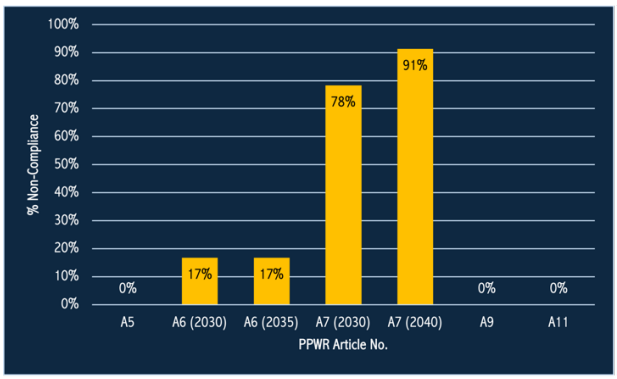


Figure 4.13 % Non-Compliance by PPWR Article.

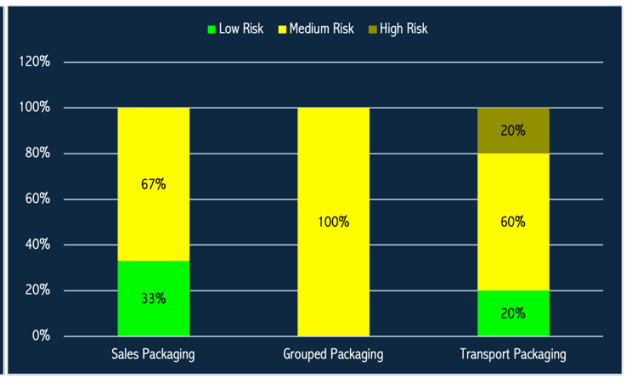


Figure 4.14 Risk distribution across packaging levels.

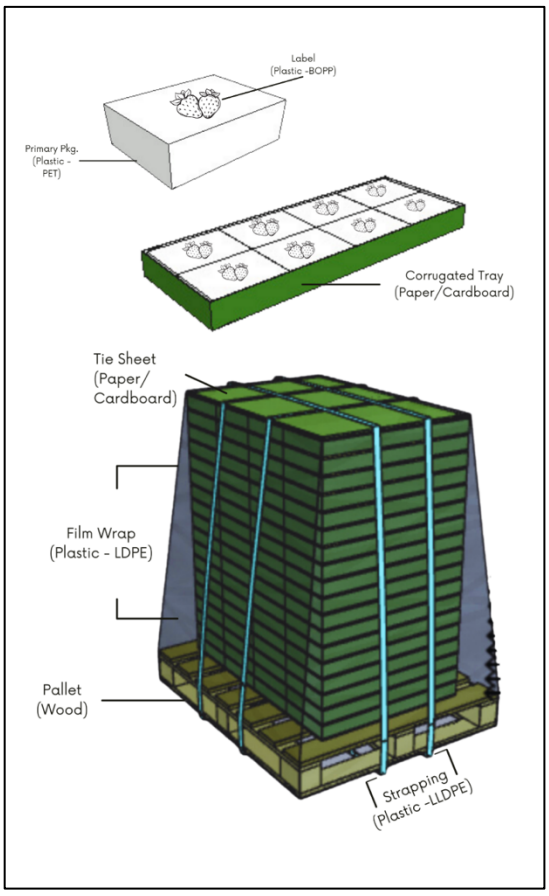


Figure 4.15 Illustrative example of packaging components across different packaging levels for specialty crops.

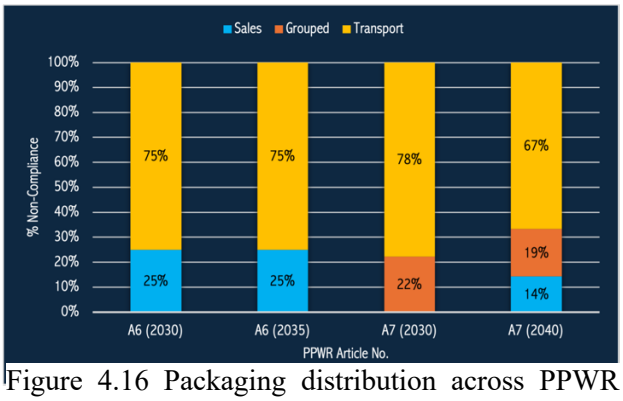


Figure 4.16 Packaging distribution across PPWR Requirement Non-Compliance.

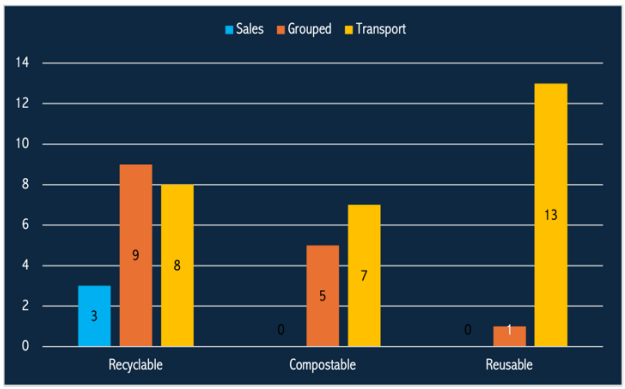


Figure 4.17 Number of Recyclable, Compostable, and Reusable Packaging per Packaging Level.

Figure 4.17 also shows the utilization of reusable and compostable packaging across various packaging levels. Reusable packaging is notably more prevalent in transport packaging than in other levels, with wooden pallets being prominent components at this tier. In contrast, compostable packaging, primarily

represented by corrugated boxes, is well-known in the grouped packaging tier. However, it is notably absent in sales packaging, where plastic materials are predominantly used.

4.3 Assessing the Impact of Polyhydroxybutyrate (PHB) on the Mechanical Recycling of Polypropylene (PP).

The study evaluated the recycling process of PP contaminated with PHB across six key regeneration stages: shredding, washing, flotation, drying, extrusion, and characterization. Each stage was assessed based on specific success criteria, and outcomes were recorded for potential impacts on material quality and processing efficiency. Table 4.1 summarizes this assessment.

Table 4.1 Impact of PHB on PP Regeneration and Use as Recycled Material.

Recycling Stage	Success Criteria	Impact
Shredding	(1) No faults or damage to the shredder during testing due to the nature of the sample; (2) No large clusters in the shredder.	No impact on shredding
Washing	(1) No soiling or jamming of equipment.	No impact on washing
Flotation	(1) The float fraction should be >90% of the total weight of the mixture; (2) No changes in the flotation water.	100% of PP ended up in the float fraction but several PHB flakes (average of 2% from 6 trials) were also detected in the float fraction with PP.
Drying	(1) No changes in the shape or appearance of flakes after drying.	No impact on drying
Extrusion	(1) No faults or damage to the extruder during testing due to the nature of the sample (accumulation, clogging, etc.); (2) Extrusion process stable during sample transformation.	The extruder operated without faults or damage throughout testing. However, during processing of the batch contaminated with PHB, an unpleasant odor was detected.
Pellet characterization	(1) Under 10% variation between control and actual samples.	*Density*: No significant impact on density *Melt Index*: No significant difference between VPP and RPP but results suggest that RPP+ PHB is significantly different from VPP, and mean values exceeds the 10% acceptable margin. *Ash content (%):* No significant difference between VPP and RPP but results suggest that RPP+ PHB is significantly different from

Table 4.1 (cont'd.).

Recycling Stage	Success Criteria	Impact
Pellet characterization (cont'd).		VPP, and mean values exceeds the 10% acceptable margin. *Melt Temperature (°C):* RPP and RPP+PHB are both within the 10% acceptable margin. *Surface Appearance*: The RPP+PHB pellets produced exhibit a darker brown hue compared to both the control and the RPP samples (Fig. 4.3).
Injection Molding	(1) No faults or damage to the machine during testing due to the nature of the sample (accumulation, clogging, etc.). (2) Molding process stable during sample transformation.	The machine operated without faults or damage throughout testing.
Molded parts characterization	(1) Reflection Color: 60<L*, -3<a*<0, -5<b*<5, DE< 5 (2) Under 10% variation between control and actual samples for mechanical properties.	*Tensile modulus:* RPP and RPP+PHB samples are both within the 10% acceptable margin *Tensile Stress at Yield:* RPP and RPP+PHB samples are both within the 10% acceptable margin. *Elongation at Yield:* RPP and RPP+PHB samples are both within the 10% acceptable margin *Tensile Stress at Break:* RPP and RPP+PHB samples fall outside the acceptable 10% margin. *Impact Strength:* *Reflection Color:* Only 35RPP met the success criteria. *Surface Appearance:* the injection molded samples produced using the PHB-contaminated PP are significantly darker than both the VPP and RPP samples.

4.4 Impact of PHB contamination on the regeneration of recycled PP

The shredding and washing stages were fine, successfully meeting all outlined criteria. However, several PHB flakes were found in the float fraction during the flotation stage. This indicates a slight inefficiency in the separation process as PHB—which typically should sink due to its higher density, as it was present in the float fraction alongside PP. This observation suggests potential compatibility challenges during flotation, which might affect the purity of the final recycled PP. Consequently, further optimization of the separation protocol may be necessary to reduce PHB levels in the PP fraction.

The drying process resulted in no discernible alterations in the morphology or appearance of the PP and PHB flakes, which is consistent with the established success criteria. Upon completion of the drying phase, an average of 2wt% PHB flakes were found in the dried float fraction across six trials. Figure 4.18 provides a mass balance illustrating the material losses during the pre-extrusion phase.

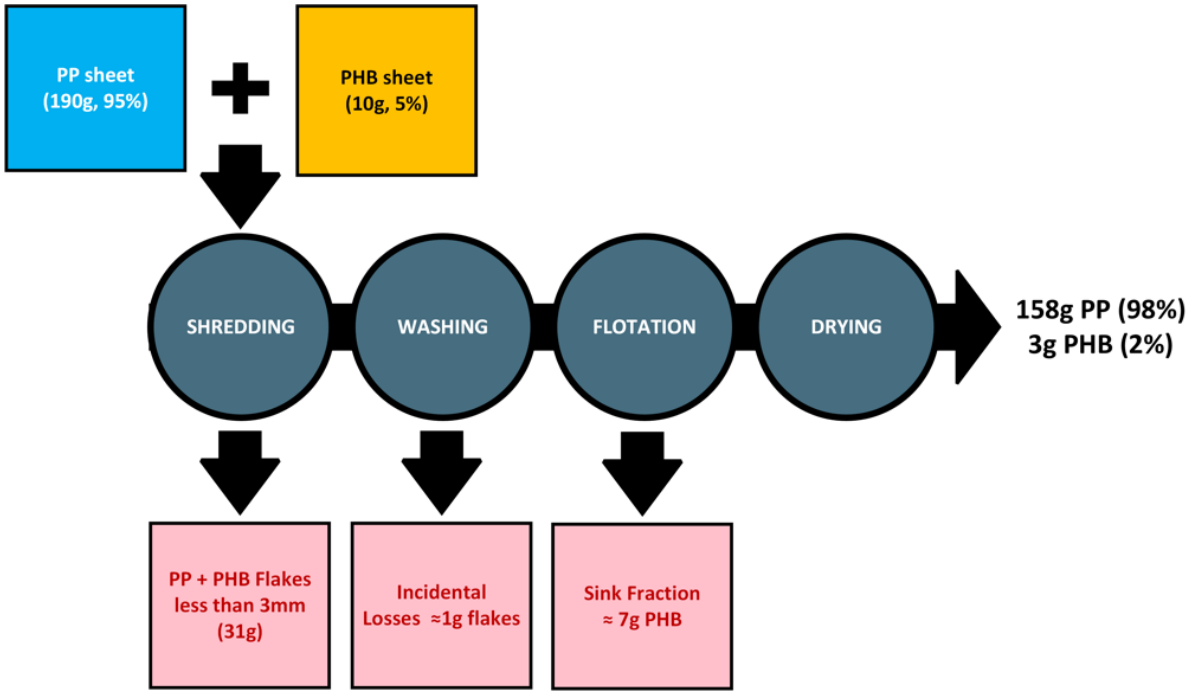


Figure 4.18 Mass Balance illustrating material losses during the pre-extrusion stage (average of 6 trials).

The extrusion phase encountered no mechanical issues. However, a significant observation was the odor emitted during the processing of the PP batch contaminated with PHB. This smell is likely due to the thermal degradation of PHB, which has a decomposition temperature range of 170-200°C. Since the extrusion processing temperature is set at 220-230°C, this exceeds the thermal stability of PHB, leading to its breakdown and resulting in the emission of an odor. Additionally, the RPP+PHB pellets exhibited a noticeable color difference compared to standard recycled PP (RPP). Figure 4.19 displays a photo that illustrates the comparison between the two.

The produced pellets—RPP and RPP+PHB—were further characterized in terms of density, melt index, ash content, and melt temperature, and then compared with the control (VPP). Results are shown in Figure 4.20. The Welch *t*-test and the Two One-Sided Test (TOST) were employed to detect significant

differences between samples and to confirm whether the values of RPP or RPP+PHB fell within a 10% acceptance margin compared to the control. Samples that are significantly different are indicated with a single blue asterisk, while those that are significantly different and exceed the 10% acceptance margin are marked with a double blue asterisk.

Figure 4.19 Produced RPP pellets contaminated with PHB (left) vs. uncontaminated RPP pellets (right).

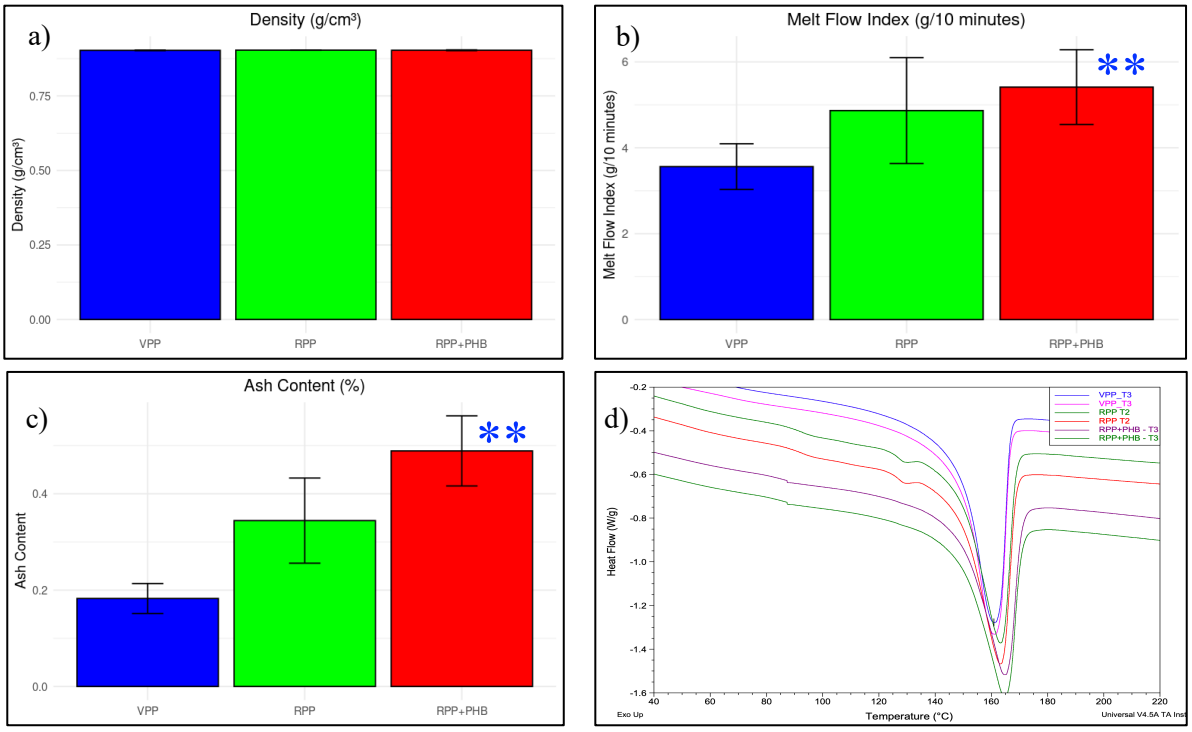


Figure 4.20 Comparison between VPP, RPP, and RPP+PHB in terms of: a) density; b) melt flow index; c) ash content; d) melt temperature; *statistically different from control; **statistically different from control and exceeds the 10% acceptance margin.

Regarding density, no statistically significant difference (t (4.39) = -1.81, p = 0.138) was observed between the control and the RPP and RPP+PHB samples, which averaged 0.903 g/cm³. Regarding the melt flow index (MFI), the Welch *t*-test results (t (2.23) = -1.78, p = 0.203) indicated no significant difference in MFI between VPP and RPP at a 95% confidence level. Likewise, the TOST results were non-significant, with a lower bound t-value of -1.32 (p = 0.847) and an upper bound of -2.25 (p=0.070), leading us to maintain the null hypothesis that the difference between VPP and RPP is within the 10% margin. In contrast, the Welch *t*-test comparing VPP and RPP+PHB revealed a significant difference (t (3.94) = -3.970, p = 0.017) at a 95% confidence level. The TOST results, reflecting a lower bound t-value of -3.42 (p= 0.986) and an upper bound of -4.52 (p = 0.006), further confirm that the difference between VPP and RPP+PHB likely exceeds the 10% margin.

In terms of ash content (%), the Welch t-test indicated that there was no statistically significant difference between VPP and RPP (t (2.49) = -2.99, p = 0.074) at the 95% confidence level. In contrast, when comparing VPP with RPP+PHB, the Welch *t*-test showed a statistically significant difference (t (2.71) = -6.71, p = 0.0093). Additionally, the TOST results for VPP versus RPP+PHB demonstrate that this difference surpasses the 10% equivalence margin, with a lower bound t-value of -6.68 (p=0.995) and an upper bound t-value of -6.73 (p=0.005).

The DSC thermogram (Figure 4.20) displays distinct melting profiles for VPP, RPP, and RPP+PHB, with notable differences between the first and second heating cycles, particularly for RPP and RPP+PHB. The melt temperatures for each sample in the first and second heating cycles are presented in Table 4.2. The melting temperature of VPP remained consistent across both heating cycles, indicating thermal stability. The melting temperature of RPP, on the other hand, decreased slightly from 163°C to 161°C, which might be due to minor structural changes such as chain scission, often observed in recycled polymers (Raghuram et al., 2023). The RPP contaminated with PHB showed a more pronounced decrease in melting temperature, from 165°C in the first heating cycle to 162°C in the second. This reduction may suggest a significant structural arrangement or change due to the presence of PHB. The Welch t-test revealed no statistically significant difference (t(2.6)=-3.18, p=0.061) in the melt temperatures of VPP and RPP for the first heating

cycle; the TOST results also showed that the difference between VPP and RPP is within the 10% acceptable margin. For VPP vs. RPP+PHB, on the other hand, the Welch t-test revealed a statistically significant difference. However, TOST results indicated that this difference is within the 10% acceptable margin.

4.5 Impact of PHB Contamination on the Usability of RPP as a Recycled Material

The injection molding machine operated without any indications of damage during testing phase, thereby meeting the set success criteria. However, a notable color discrepancy was observed between the VPP and RPP+PHB samples, as illustrated in Figure 4.21.

Just to reiterate, the chosen sample compositions reflect the PPWR recycled content requirements for plastic packaging for 2030 and 2038/2040, maintaining standards of 35% and 65% recycled content, respectively. Average color measurements for the samples are presented in Table 4.3. In examining the ΔE values, it is noted that only 35RPP met the success criteria, with 65RPP being close to passing. However, for the RPP+PHB samples, the ΔE values are significantly high.

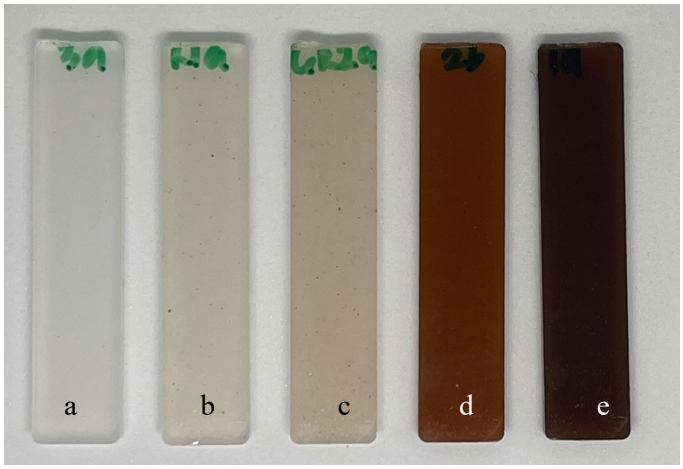


Figure 4.21 Molded samples: a -VPP; b – 35RPP;
c – 65RPP; d – 35RPP+PHB; e – 65RPP+PHB.

Table 4.2 Color Measurement Results.

Sample	***L****	***a****	***b****	**ΔE**
VPP (Control)	67.5	-0.4	7.7	-
35RPP	66.1	0.2	10.4	3.1
65RPP	60.2	0.9	12.4	8.8
35RPP+PHB	25.9	16.0	29.2	49.6
65RPP+PHB	12.8	9.4	12.2	55.8

Table 4.3 Tensile Test Results.

	VPP	35RPP	65RPP	35RPP+PHB	65RPP+PHB
Tensile Stress at Yield (MPa)	61.5 ± 1.6	64.6 ± 1.9*	68.3 ± 1.7*	65.4 ± 2.2*	66.4 ± 1.5*
Elongation at Yield (%)	26.9 ± 0.0	28.7 ± 0.0*	37.9 ± 0.1*	39.7 ± 0.0*	37.1 ± 0.0*
Tensile Stress at Break (MPa)	61.5 ± 4.9	68.9 ± 4.6**	76.2 ± 5.6**	70.4 ± 4.0**	70.7 ± 4.1**
Elongation at Break (%)	909.7 ± 223.4	1910.3 ± 196.2**	1311.0 ± 222.0**	1202.6 ± 149.2**	1176.8 ± 208.9**
Tensile Modulus (MPa)	745.7 ± 49.7	747.4 ± 57.5*	573.5 ± 93.9*	443.1 ± 77.0*	486.1 ± 56.9*

*statistically different from control; **statistically different from control and exceeds the 10% acceptance margin.

Table 4.4 Impact Test Results.

Sample	Impact Strength (J/m)	Impact Strength (kJ/m^2)
VPP (Control)	C: 558.0 ± 0.0 (20%) H: 280.3 ± 178.5 (80%)	C: 54.7 ± 0 (20%) H: 27.5 ± 17.5 (80%)
35RPP	C: 231.0 ± 163.5 (80%) H: 19.0 ± 0.0 (20%)	C: 22.7 ± 16.1 (80%) H: 1.9 ± 0.0 (20%)
65RPP	C: 186.3 ± 88.9 (100%)	C: 18.3 ± 9.8 (100%)
35RPP+PHB	C: 206.0 ± 196.9 (100%)	C: 20.2 ± 19.3 (100%)
65RPP+PHB	C: 32.4 ± 12.5 (100%)	C: 3.2 ± 1.2 (100%)

Table 4.4 summarizes the mechanical properties of injection-molded VPP, RPP, and RPP blends contaminated with PHB. As observed, the data indicate that incorporating RPP typically enhances the tensile stress at yield, elongation at yield, tensile stress at break, and elongation at break, while having the opposite effect on the tensile modulus. The results somewhat deviate from what is reported in various literature, as RPP generally exhibits a decrease in tensile strength and elongation at break (Aurrekoetxea & Urrutibeascoa, 2001; da Costa et al., 2004; Main et al., 2023; Schyns & Shaver, 2020). Similar but less pronounced effects were observed in RPP+PHB samples. These findings suggest further investigation is necessary to understand this underlying cause of deviation. Nevertheless, we continued our assessment to determine whether these results still meet the success criteria. Statistical analysis using one-way ANOVA with post-hoc Tukey's HSD revealed significant differences across all measured parameters for comparisons between VPP and each of the following groups: 35RPP, 65RPP, 35RPP+PHB, and 65RPP+PHB. Furthermore, TOST analysis showed that the sample means for tensile stress at yield,

elongation at yield, and tensile modulus were within the acceptable 10% margin. However, for tensile stress at break and elongation at break, the observed effects exceeded this margin, failing to meet the success criteria. Table 4.5 presents a summary of the Izod impact test results. A general downward trend in impact strength is noted with the addition of RPP and further with RPP contaminated with PHB. The findings align with existing literature; however, the high standard deviation may complicate drawing definitive conclusions (Aurrekoetxea & Urrutibeascoa, 2001; da Costa et al., 2004; Main et al., 2023; Schyns & Shaver, 2020).

CHAPTER 5: CONCLUSIONS & RECOMMENDATIONS

5.1 Conclusions

This study had two main objectives: first, to create a Compliance Assessment Tool (CAT) to evaluate the risks and threats U.S. specialty crop exporters might face when exporting to the European Union under the recently approved Packaging and Packaging Waste Regulation (PPWR). Second, it aimed to analyze the impact of poly(3-hydroxybutyrate) (PHB) contamination on the mechanical recycling of polypropylene (PP) packaging, considering the PPWR's emerging requirements for biodegradable plastics.

The research methodology for Study 1 comprised several essential steps: 1) reviewing and identifying the primary PPWR packaging requirements as well as review of other related packaging regulations; 2) collecting information about the packaging systems utilized by U.S. exporters of specialty crops to the European Union; 3) creating and developing an algorithm for the compliance assessment tool; and 4) classifying risks and identifying packaging systems impacted by the new EU regulation. We assessed twenty-nine (29) packaging units, which included 45 packaging components. While this initial assessment was promising, we faced challenges in recruiting additional companies, primarily due to their hesitance to share information.

Through the development and application of the compliance assessment tool (CAT), we pinpointed key packaging systems likely to be affected by the PPWR. Our findings indicate that U.S. specialty crop exporters may encounter compliance challenges related to the recycled content and recyclability requirements set by the PPWR. Notably, transport packaging systems are significantly impacted due to their material complexity, which complicates compliance. It is important to acknowledge certain limitations in this assessment, such as potential inaccuracies stemming from participants' survey responses. Since these responses were self-reported, varied interpretations or misunderstandings could lead to over- or under-reporting of compliance issues. The tool we have developed serves as an essential resource., aiding exporters in streamlining the risk assessment process for packaging compliance with evolving regulations. Although it was specifically designed for the PPWR, its framework and methodology could also serve as a model for creating similar tools relevant to other packaging regulations.

The second phase of the study examined the effects of PHB contamination in PP recycling streams. The study was conducted in two stages: 1) the Regeneration Phase, in which we replicated the mechanical recycling conditions (shredding, washing, flotation, and extrusion) in the lab according to the Recyclass® protocol; and 2) evaluating the usability of the regenerated RPP pellets through injection molding, followed by a characterization of the resulting injection molded parts.

Results indicate that while PHB contamination did not notably disrupt the technical aspects of shredding, washing, or extrusion, it introduced minor complications at the flotation stage, where trace amounts of PHB flakes remaining in the PP float fraction. More critically, during the extrusion and pellet characterization, PHB contamination influenced specific material properties: the recycled PP (RPP) + PHB pellets demonstrated alterations in coloration and odor, along with variations in mechanical properties such as melt index and ash content exceeding acceptable thresholds in comparison to virgin PP. While tensile modulus, stress at yield, and elongation at yield remained within acceptable limits, the tensile stress and elongation at break were below the acceptable threshold. This indicates a possible compromise in material quality when packaging converters process PHB-contaminated PP for use as recycled material.

These findings underscore the necessity of considering the compatibility of PHB with traditional recycling streams. This consideration is particularly pertinent given the rising demand for biobased and biodegradable plastics such as PHB. Furthermore, the current absence of waste receptacles specifically designed for biodegradable and compostable plastics presents a significant challenge. As the usage of these materials is anticipated to increase markedly in the coming years, there exists a substantial risk that they will inadvertently enter the recycling streams intended for commonly recycled polymers, compromising recycling initiatives.

5.2 Recommendations for future work

Developing the Compliance Assessment Tool (CAT) presented challenges due to outdated standards for assessing packaging requirements like recyclability and the ambiguity in legal texts. Clear definitions and criteria are essential for effective compliance evaluation, and validation by EU authorities is crucial to ensure the tool's accuracy. Future work should expand the CAT's applicability to other

regulatory environments to enhance its utility and keep it updated with evolving legal interpretations. Regular collaboration with industry stakeholders and regulatory bodies will be vital to maintain alignment with changing packaging regulations.

Our results from tensile tests on injection-molded parts—VPP, 35VPP, 65VPP, 35RPP+PHB, and 65RPP+PHB—revealed unexpected deviations from reported literature. Unlike typical findings, our data indicate that adding RPP typically enhances tensile stress at yield, elongation at yield, tensile stress at break, and elongation at break, but reduces tensile modulus. This contrasts with past research, which often reports a decrease in tensile strength and elongation at break with RPP (Aurrekoetxea & Urrutibeascoa, 2001; da Costa et al., 2004; Main et al., 2023; Schyns & Shaver, 2020) (Aurrekoetxea & Urrutibeascoa, 2001; da Costa et al., 2004; Main et al., 2023; Schyns & Shaver, 2020). We also noted similar, though less pronounced, effects in the RPP+PHB samples, underscoring the necessity for further exploration to understand the cause of this discrepancy.

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APPENDIX A: FLYERS DISTRIBUTED TO SPECIALTY CROP EXPORTERS

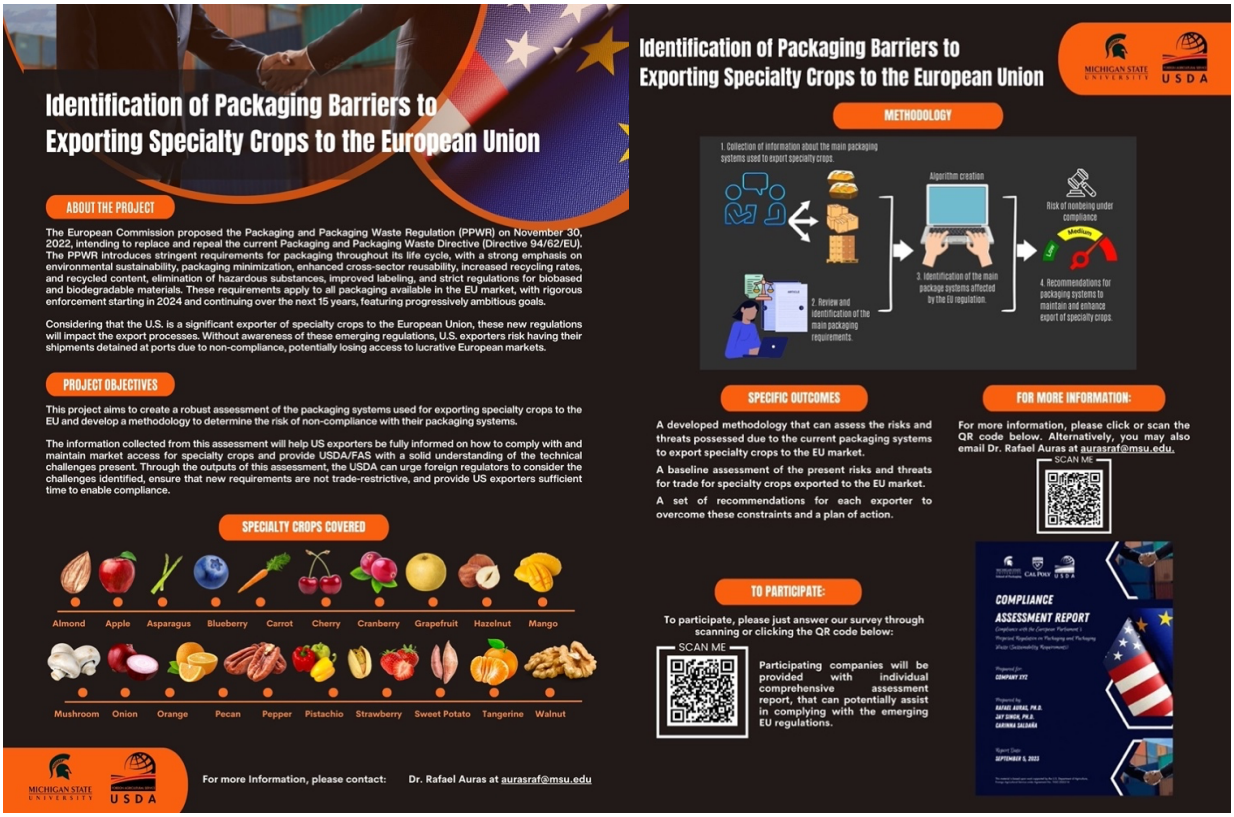

Figure A.1 Flyers distributed to exporters of specialty crops to the European Union.

APPENDIX B – QUALTRICS SURVEY DISTRIBUTED TO SPECIALTY CROP EXPORTERS

qualtrics XM

USDA / MSU Survey on Packaging Systems for Specialty Crops - v.2
Survey Flow

Standard: Block 3 (4 Questions)
Standard: PRIMARY PACKAGING (12 Questions)
Standard: SECONDARY PACKAGING (12 Questions)
Standard: TERTIARY PACKAGING (12 Questions)

Start Block: Block 3

Q106 ***USDA / MSU Survey on Packaging Systems for Specialty Crops***

Thank you for taking the time to participate in our survey. This survey aims to gather baseline information about the current packaging system used to export specialty crops to the European Union. The information collected from this assessment will help US exporters be fully informed on how to comply with and maintain market access for specialty crops and provide USDA/FAS with a solid understanding of the technical challenges present. Through the outputs of this assessment, the USDA can urge foreign regulators to consider the challenges identified, ensure that new requirements are not trade-restrictive, and provide US exporters sufficient time to enable compliance.

Please be assured that your responses will remain confidential and only be used for research purposes. All data collected will only be published and presented in an aggregated form, without any identifiable information about individual participants. If you have any questions, please get in touch with Dr. Rafael Auras at aurasraf@msu.edu or Carinna Saldaña at saldan21@msu.edu.

Q98 *Name of Company:*

_____

Q210 Company Size
Small (10 to 49 employees) (1)
Medium (50 to 249 employees) (2)
Large (250 or more employees) (3)
Q99 Product/ Specialty Crop:
▼ Almond (4) ... Walnut (23)
End of Block: Block 3

Start of Block: PRIMARY PACKAGING

Q110 ***Primary Packaging*** refers to the package which is in direct contact with the product. A primary package can be composed of not just the material touching the product. It also includes the label, lid or cap (of a bottle or container), or tape used to seal the product. We will refer to them as "component" in this survey.

Q102 *Please attach photo of product in primary package:*

Q76 *Overall Primary Package Dimensions (L x W x H), in inches:*

Q78 *Net weight of product (in grams):*
Q109 How many individual components are part of the primary package?
▼ 1 (1) ... 6 (7)
Q109 Please specify the component (i.e., label, film, cap, tie, tape, strap), the material of the component (i.e., LDPE, HDPE, PET, paper, composite/ multilayer), weight, and % recycled content of the component, if applicable.

	Type of Material (1)	Weight (in grams) (2)	Presence of lead, mercury, cadmium, or hexavalent chromium? (Yes, No, or I don't know) (4)	Recyclable? (5)	Recycled content (%) (6)
⊗Component 1.: (1)					
⊗Component 2: (2)					
⊗Component 3: (3)					

Q11 Is the primary packaging re-usable?
Yes (please specify the number of re-use times): (1)
No (2)
I don't know (3) _____
Skip To: Q83 If Is the primary packaging re-usable? = Yes (please specify the number of re-use times below):
Skip To: Q13 If Is the primary packaging re-usable? = No
Skip To: Q13 If Is the primary packaging re-usable? = I don't know
Q83 Is an appropriate system, necessary to support reuse, available at the target market (EU)?
Yes (1)
No (2)

Other (3) _____
Q13 As a unit, is the primary packaging recyclable?
Yes (1)
No (2)
I don't know (3) _____

Skip To: Q85 If As a unit, is the primary packaging recyclable? = Yes

Skip To: Q86 If As a unit, is the primary packaging recyclable? = No

Skip To: Q86 If As a unit, is the primary packaging recyclable? = I don't know

Q85 Is the packaging material compatible with known and relevant industrially available recycling technologies?
Yes (1)
No (2)
Other (3) _____

Q86 Is the primary packaging recoverable in the form of energy?
Yes, organic content > 50% by weight (1)
Yes, inorganic content > 50% by weight (2)
No (3)
Other: (4) _____

Q87 Is the primary packaging compostable?
Yes (1)
No (2)
Other: (3) _____

End of Block: PRIMARY PACKAGING
Start of Block: SECONDARY PACKAGING

APPENDIX C – SAMPLE REPORT PROVIDED TO SPECIALTY CROP EXPORTERS

Figure C.1 Cover Page of the Report provided to Specialty Crops Exporters.

DISCLAIMER

Any opinions, findings, conclusion, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the view of the U.S. Department of Agriculture.

Michigan State University and the School of Packaging shall not be held liable for the assessment provided herein, as this assessment is intended solely as early guidance information to companies exporting specialty crops to the European Union (EU) to meet the new regulatory requirements of the EU on packaging.

Additionally, it is essential to acknowledge that the information provided in this report is based on the draft proposed Packaging and Packaging Waste Regulation (PPWR) published by the European Commission on November 30, 2022, and updated to reflect the November 2023 version of the PPWR proposal, incorporating amendments considered by relevant committees before the European Parliament's adoption of its position on the regulation. Due to the dynamic nature of the regulatory process, the information presented here may be subject to updates and revisions. While this report provides a snapshot of the regulatory landscape based on the latest available information, stakeholders should remain attentive to any further developments in the legislative process.

EXECUTIVE SUMMARY

The proposed Packaging and Packaging Waste Regulation (PPWR), intended to replace and repeal the outdated Directive 94/62/EU (Packaging and Packaging Waste Directive), will introduce stringent requirements for packaging throughout its lifecycle. These requirements will prioritize environmental sustainability, packaging minimization, enhanced cross-sector reusability, increased recycling rates, promotion of recycled content, elimination of hazardous substances, improved labeling, and strict regulations for biobased and biodegradable materials. Applicable to all packaging available in the EU market, these requirements will be subject to rigorous enforcement scheduled to commence in Q1 2025, continuing over the following 15 years with progressively ambitious goals.

Considering that the U.S. is a significant exporter of specialty crops to the European Union, these new regulations will impact the export processes. Without awareness of these emerging regulations, U.S. exporters risk having their shipments detained at ports due to non-compliance, potentially losing access to lucrative European markets.

Through the project "Identification of Packaging Barriers to Exporting Specialty Crops to the European Union," the packaging systems used by Company ABC for exporting apples to the EU were assessed to determine the risk of its non-compliance with the new regulations.

Based on the data submitted by the company and the stipulations outlined in the proposed PPWR, the assessment concludes that ….

ABOUT THE PROPOSED PACKAGING AND PACKAGING WASTE REGULATION (PPWR)

On November 30, 2022, the European Commission introduced a proposed regulation to address packaging and packaging waste comprehensively. This regulation builds upon the existing legislative framework and seeks to repeal Directive 94/62/EU, also known as the Packaging and Packaging Waste Directive (PPWD).

The proposed regulation establishes requirements for packaging throughout its entire life cycle, including environmental sustainability and labeling for market placement. It also sets minimum standards for extended producer responsibility, collection, treatment, and recycling of packaging waste, with corresponding reporting obligations. These requirements apply to all packaging placed on the market in the European Union.

The objectives of this proposed regulation are twofold: to contribute to the efficient functioning of the internal market while preventing or reducing adverse environmental and health impacts of packaging and to protect the environment and human health by addressing the generation and management of packaging waste.

The revision of the directive aims to update and establish concrete, effective, and easily implementable provisions to foster sustainable packaging in the internal market. It aims to minimize complexity, promote economically feasible solutions, enhance reusability and recyclability, and reduce the presence of substances of concern in packaging materials, particularly for food packaging. Additionally, it intends to introduce clear and easily understandable labeling on packaging to inform consumers about recyclability and proper disposal methods for recycling. By becoming a regulation, it ensures consistent and homogeneous implementation of rules across all member states.

This transition to regulation eliminates the need for EU importers to comply with the varying requirements of individual member states. The new regulation's earliest potential time of enactment is early 2025, necessitating economic operators in the EU to start preparing for its implementation.

In the proposed regulation, manufacturers importing and/or operating in the EU must comply with the sustainability and labeling requirements stated in Articles 5 to 11.

- Article 5 lists restrictions on using substances of concern in packaging, particularly lead, cadmium, mercury, and hexavalent chromium, as well as prohibiting the use of food packaging materials with intentionally added PFAS and/or BPA.
- Article 6 requires packaging to be recyclable and sets out what requirements must be met in a two-stepped approach.
- Article 7 requires that, as of January 1, 2030, the plastic part in packaging (unless it results to non-compliance with food safety requirements laid down at Union level) contain a certain minimum amount of recycled content recovered from post-consumer plastic waste per packaging. These amounts shall increase by January 1, 2040.
- Article 8 defines conditions for packaging to be considered compostable (home composting standards or industrially controlled conditions) and prescribes that filter coffee pods are disposed of together with the used coffee products, and sticky labels attached to fruits and vegetables, as well as very lightweight plastic carrier bags be compostable by 36 months after entry into force of the regulation.

Article 9 requires that the weight, volume, and layers of packaging should be minimized with due account taken of the packaging's safety and functionality. Thresholds for sales packaging in specific sectors, grouped packaging, and transport packaging are listed.

Article 10 lays down the requirements for reusable packaging. One of the requirements is for example that the packaging is conceived, designed, and placed on the market to be re-used or refilled a maximum number of times.

Article 11 pertains to packaging label requirements, which include requirements such as, but not limited to, requiring the label to contain information on its material composition, recycled content in plastic packaging, and requiring reusable packaging to bear a QR code giving access to relevant information facilitating its re-use.

ABOUT THE MSU-USDA PROJECT "IDENTIFICATION OF PACKAGING BARRIERS TO EXPORTING SPECIALTY CROPS TO THE EUROPEAN UNION"

This project aims to assess the primary, secondary, and tertiary packaging being used to export specialty crops (i.e., almonds, pistachios, pecans, walnuts, hazelnuts, sweet potatoes, asparagus, onion, mushroom, grapefruit, tangerine, mango, cranberry, peppers, cherries, oranges, blueberries, strawberries, apples, and carrots) to the European Union and develop a methodology to determine the risk of non-compliance of these packaging systems to the new EU regulations.

The primary outcomes of this project are:
a developed methodology that can assess the risk and threats possessed due to the current packaging systems to export specialty crops to the EU market,
a baseline assessment of the present risk and threats for trade for the main specialty crops, and
a set of recommendations to overcome these constraints, and a plan of action.

The information collected from this assessment will help US exporters be fully informed on how to comply with and maintain market access for specialty crops and provide USDA/FAS with a solid understanding of the technical challenges present. Through the outputs of this assessment, the USDA can urge foreign regulators to consider the challenges identified, ensure that new requirements are not trade-restrictive, and provide US exporters sufficient time to enable compliance.

The methodology for this project involved several key steps. Firstly, information was collected regarding the primary, secondary, and tertiary packaging systems currently used for exporting specialty crops. This encompassed gathering data on packaging materials, designs, and specifications commonly employed in the industry. Secondly, a comprehensive review was conducted to identify the main packaging requirements outlined in the Packaging and Packaging Waste Directive and the PPWR. These requirements were carefully analyzed, focusing on sustainability, restrictions on substances of concern, recyclability, reuse, and labeling obligations.

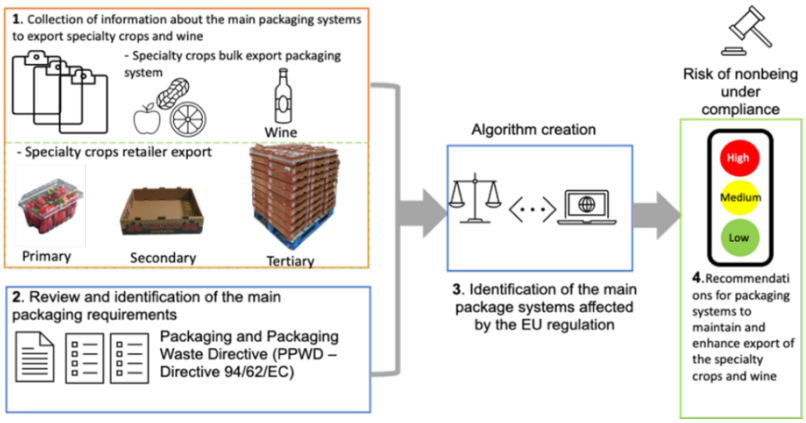

Figure C.2. Methodology of the project.

Next, an algorithm or framework was developed to assess how the EU regulations affect different packaging systems. Factors such as packaging type, materials used, recyclability, and compliance with specific requirements were considered. This algorithm served as a tool to evaluate and classify packaging systems based on their alignment with EU regulations.

Following the algorithm creation, a risk assessment was conducted to determine the level of compliance and potential risks associated with non-compliance for the assessed packaging systems. Areas, where the existing packaging systems may fall short of EU regulatory requirements were identified. Based on these findings, recommendations and strategies were developed to enhance the packaging systems, ensuring their alignment with EU regulations, and facilitating the export of specialty crops. These recommendations include modifications, materials substitution, labeling improvements, and other measures necessary to achieve compliance and maintain market access.

LIMITATIONS OF THE ASSESSMENT

The assessment was confined to the specific questions that were asked, chosen to ensure ease of response for the participants. Also, the summary of the assessment is only provided for the described primary, secondary, and tertiary packaging as presented in Section IV, based on information provided by the respondent.

It is further important to note that the information provided in this report is based on the draft version of the PPWR published by the European Commission on 30 November 2022, further updated to reflect the November 2023 version of the PPWR proposal. As the regulatory process is continuously evolving, the information presented here may be subject to updates and revisions. Therefore, this assessment should be utilized solely as guidance. Moreover, it is essential to acknowledge that the survey/assessment did not encompass the requirements outlined in Article 9 and 11 of the PPWR. Nevertheless, these requirements are addressed in the recommendations section for consideration.

ASSESSMENT FINDINGS

Table C.1 Packaging Material Assessed.

Primary Packaging (PP)	Secondary Packaging (SP)	Tertiary Packaging
Type:	Type:	Type:
Material:	Material:	Material:
Overall Dimension:	Overall Dimension:	Overall Dimension:
Weight:	Weight:	Weight:
Recycled Content:	Recycled Content:	Recycled Content:
Photo	Photo	Photo

Table C.2 Summary of the Assessment.

Category	E.U. Requirement	PP	SP	TP
Restrictions on Substances of Concern in Packaging	xxx			
Recyclability	xxx			
Minimum recycled content in plastic packaging	xxx			
Compostability	xxx			
Packaging minimization	xxx			
Reusability	Xxx			
Package Label	xxx			
Risk Level				

Zero (0) corresponds to a favorable response, indicating that the packaging unit is compliant, whereas One (1) corresponds to an unfavorable response, indicating that the packaging unit is non-compliant.

CONCLUSION

xxx

RECOMMENDATIONS

xxx

APPENDIX D – IRB EXEMPTION

MICHIGAN STATE UNIVERSITY

DETERMINED NOT "HUMAN SUBJECTS"
Revised Common Rule

November 9, 2023

To: Rafael Auras

Re: **MSU Study ID:** STUDY00009918
Principal Investigator: Rafael Auras
Determination Date: 11/9/2023

Title: Identifying packaging barriers to exporting specialty crops and wine to the European Union

Grant Title: Impact of the new EU packaging waste directive on the U.S. specialty crops trade
Sponsor: Foreign Agricultural Service
Status: Funded

The activity described in this submission was determined not to involve "human subjects" as defined by the Common Rule as codified in the U.S. Department of Health and Human Services (DHHS) regulations for the protection of human research subjects.

Definition of Human Subject
For DHHS, "*Human subject* means a living individual about whom an investigator (whether professional or student) conducting research:

(i) Obtains information or biospecimens through intervention or interaction with the individual, and uses, studies, or analyzes the information or biospecimens; or

(ii) Obtains, uses, studies, analyzes, or generates identifiable private information or identifiable biospecimens." [45 CFR 46.102(e)(1)]

Determination
The survey asks questions about packaging and not about the living individual. The study team will not collect any identifiable information from subjects.

Hence, the activity does not involve human subjects.

Therefore, the federal regulations for the protection of human subjects would not apply to this activity and Michigan State University (MSU) Institutional Review Board (IRB) approval is not needed to proceed. However, please note that while MSU IRB approval is not required, other federal, state, or local regulations or requirements or ethical or professional standards may still be applicable based on the activity.

Office of Regulatory Affairs
Human Research Protection Program

4000 Collins Road
Suite 136
Lansing, MI 48910

517-355-2180
Fax: 517-432-4503
Email: irb@msu.edu
www.hrpp.msu.edu

Figure D.1 IRB Exemption Letter (1st page).

Modifications: If any of the activities described in this submission change, please contact the IRB office as the activity may involve human subject research and require IRB approval. For example, this determination is not applicable to activities that may be regulated by U.S. Food & Drug Administration (FDA), such as those involving drugs, medical devices, human food additives, color additives, electronic products, or any other test articles regulated by the FDA.

Modifications to Funding: **Changes in funding may alter this determination.** For example, MSU IRB review and approval is required if MSU receives an award through a grant, contract, or cooperative agreement directly from a federal agency, even where all non-exempt research involving human subjects are carried out by employees or agents of another institution. In addition, the new funding source may have additional or different requirements.

For More Information: See HRPP Manual Section 4-3, Determination of Human Subject Research (available at hrpp.msu.edu).

Contact Information: If we can be of further assistance or if you have questions, please contact us at 517-355-2180 or via email at IRB@msu.edu. Please visit hrpp.msu.edu to access the HRPP Manual, templates, etc.

Figure D.2 IRB Exemption Letter (2nd page).

APPENDIX E: CONFERENCE PRESENTATIONS, SEMINARS, AND PUBLICATION GENERATED FROM THIS THESIS

- Saldaña-Pierard, C., Auras, R., Stephens, A., Singh, J., & Almenar, E. (2024, June 20). *In the Face of Change: Developing a Tool to Assess Packaging System Compliance with Emerging Regulations*. 24th IAPRI World Packaging Conference, Valencia, Spain (Oral Presentation)
- Webinar presentation for U.S. Specialty Crop Exporters: Auras, R., & Saldaña-Pierard, C. (2024, March 29). *Navigating EU Packaging Regulations: Ensuring Compliance for Specialty Crop Exporters*.
- Publication in the Journal of Industrial Ecology (pending submission): Saldaña-Pierard, C., Nguyen, P. M., Debeaufort, F., Vitrac, O., & Auras, R. (n.d.). *Impact of Emerging Packaging Regulations on International Trade and Product Safety with Emphasis on Plastic Reuse and Recycling*