Evaluate the effectiveness of bio-nanotechnologies, both natural and engineered, to apply circular economy principles in the plastic-dominant food packaging industry.

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Introduction

The following dissertation evaluates the effectiveness of biotechnological applications to apply circular economy principles in the plastic food packaging market. Plastic accounts for one-third of the global packaging market: a 700-billion-a-year industry (Leahy, 2019) . Plastic is incredibly wasteful due to the linear, 'take-make-waste' model of packaging: it is often designed for single-use and to be thrown away almost immediately. According to the *Ellen McArthur Foundation* (Plastics and The Circular Economy, n.d.), millions of tons of plastic, worth billions of dollars, end up in landfills, burned, or leaked into the environment annually. In addition, scientists theorize that there will be more plastic in the ocean than fish by 2050 (Plastics and The Circular Economy, n.d.).

Although concerns about food packaging are often centered on plastic specifically, plastic packaging is also one of the most important contributors to preventing food waste which has at least ten times the environmental impact of packaging waste (*Why Do We Need Plastic Packaging?*, 2021).

Fig. 1.1 Graph of environmental impact of packaging vs. food waste (cited from *British Plastics Federation*)

Plastic packaging is a 'double edged sword:' it is a solution to another more devastating problem. Food takes considerably more resources to create than plastic packaging, and "makes environmental sense to protect it for as long as possible so the resources invested in its growth are not invested in vain" (*Why Do We Need Plastic Packaging?*, 2021). Despite plastic's devastating effects on the environment, it exists to protect and preserve food for longer, allow transport over great distances, and therefore prevent food waste. The different functions of plastic are important and even *needed* in the food packaging industry.

In a circular economy for plastics, plastic never becomes waste – instead, it is recycled or reused. In food packaging, a circular economy of plastics would allow plastic to continue contributing to the prevention of food waste, without polluting the environment with microplastics. According to the *Ellen McArthur Foundation*, three important actions need to come into effect to achieve a circular economy of plastics. Therefore, each chapter will evaluate how biotechnological applications will help accomplish each one of those goals.

The first goal is the elimination of 'unnecessary or problematic' plastic food packaging. According to the *Ellen McArthur Foundation* (*Plastics And The Circular Economy*, n.d.), "sometimes plastic packaging can be avoided altogether while maintaining utility." Therefore, the first chapter evaluates how biotechnology can eliminate plastic altogether in food packaging through biological breakdown methods and the use of bio-alternatives. Firstly, biological breakdown methods (e.g. fungi, enzymes, etc.) can *decompose* pre-existing plastic that pollutes the environment will be evaluated on their breakdown capabilities and feasibility. Secondly, biodegradable 'plastics' made of biomaterials will be evaluated as a replacement to fossil-based plastic in short shelf-life foods, as they do not need the long-lasting performance of plastics. Lastly, biodegradable packaging's sustainability will be assessed, by comparing it to recyclable plastic.

The second goal is the *innovation* of 'necessary plastics' to be recyclable and *circulated* in the economy. Unfortunately, the president of the *Association of Plastic Recyclers* Steve Alexander, claims that "the enormous variety and abundance of plastic packaging is problematic for the recycling industry" – even if plastic is recyclable, it does not mean it will be recycled (Leahy, 2019). For example, clamshells, like most packaging, are single-use plastics and while technically recyclable, "few are recycled in the US" (Leahy, 2019). Therefore, the second chapter evaluates how biotechnology can simplify the complex infrastructure of recycling by streamlining the collection and segregation processes of packaging materials. With proper material circulation, plastic packaging will prevent food waste, but without polluting the environment with plastic.

The third goal is the innovation and re-design of packaging attributes through active packaging, which have the potential to positively influence "user behavior with regard to food losses, recycling and cleaning" (Wikström et al., 2016). Direct environmental impacts of packaging, such as the production of packaging materials and end-of-life treatment, do not determine a package's sustainability. According to the *Journal of Clean Production* (Wikström et al., 2016), indirect environmental impacts which are related to user behaviors and attitudes "are more important for the environmental outcome than the direct impact of packages." Thus, the third chapter begins by conducting a full-life cycle analysis of two packages to establish the importance of packaging attributes influence on indirect environmental impacts. Then, active packaging attributes will be evaluated on their ability to alleviate the generation of food loss at the hands of the consumer. Lastly, user perceptions regarding nanotechnology are analyzed due to existing hesitancies to this new domain of packaging.

Chapter 1 – Elimination and Replacement of 'Unnecessary' Plastic Packaging

According to the *Ellen McArthur Foundation* (*Plastics And The Circular Economy*, n.d.), a circular economy for plastics requires the elimination of problematic and unnecessary plastic items. Chapter two evaluates how biotechnologies can aid the elimination and replacement of plastic in the food packaging industry.

Section 1.1 explores biological breakdown methods derived from living fungi, capable of decomposing fossil-based plastic. Section 1.2 explores biodegradable 'plastic' made of biomaterials, with potential to replace plastic packaging for products with short shelf-lives. Lastly, section 1.3 evaluates to what extend is biodegradable 'plastic' more sustainable than oil-derived plastics.

1.1 Elimination of Plastic Packaging via Biological Breakdown Methods

Biotechnology is defined as "the branch of applied science that uses living organisms and their derivatives to produce products and processes"(Kagan, 2021). Biological breakdown derivatives found in living organisms can *decompose* and therefore eliminate plastic, including and not limited to fungi, bacteria, and enzymes. While the decomposers natively appear in a variety of natural environments, the chapter evaluates their applications in the future through artificial production and the capitalization of their regenerative properties.

1.1.1 Fungi transform plastic into organic matter

Fungi are one of many nature's decomposers which play a crucial role for the recycling of nutrients in ecosystems. Fungi have a derivative called mycelia, also known as the vegetative part of a fungus consisting of "a network of fungal threads, or hyphae" (*Mycelium*, n.d.). Mycelia can break down and absorb nutrients from its environment as it grows, typically from organic matter such as woodland resources, food, manure, and by-products from agricultural operations. Nevertheless, scientists began to discover species of fungi that can produce catalysts (enzymes) capable of degrading polyurethane and converting it into organic matter. The fungus is called *Pestalotiopsis Microspora and* is natively found in the Amazon rainforest (Steffen, 2019). Below is an image of a prototype called *Fungi Mutarium* conducted by Katharina Unger of Utrecht University, which aimed to see which mushrooms are capable of decomposing polyurethane.

Fig. *1.2* Prototype *Fungi Mutarium* conducted by Katharina Unger of Utrecht University (cited from *Intelligent Living*)

The experiment revealed that the Amazonian fungus is not the only one capable of digesting plastic. The oyster mushroom, a common, edible mushroom, can also eat plastic. Unger confirmed that the oyster mushroom broke down all the plastic and converted it into mycelium (Steffen, 2019).

Fascinatingly, fungal spores have regenerative properties: a single spore can grow into mycelia over time and under the right conditions, allowing it to accumulate by itself over time. Scientists believe that the fungus can be applied to tackle plastic pollution on an industrial scale, by inoculating landfills with *Pestalotiopsis Microspora* spores to degrade plastic by their own. The fungus can also live without oxygen, which is suitable considering landfills are compact environments with a lack of oxygen (Steffen, 2019). In addition, once polyurethane is converted into organic matter, it is edible, nutrient-rich, and thus a proposed solution to hunger crises.

Despite fungi's abilities to decompose, the technology poses several limitations. Mycelia grow faster when exposed to limited oxygen, high temperatures, darkness, and humidity. Without the proper conditions, mycelial growth stagnates, making it susceptible to contamination and eventually death. Therefore, a controlled environment (e.g., laboratory) is advised for the best of outcomes, as seen in *Fungi Mutarium,* and would be ineffective in landfills and other outdoor environments. Therefore, more research is required for any landfill applications.

As stated in the previous paragraph, the unpredictable conditions in outdoor environments including landfills make mycelium susceptible to contamination and death. Fascinatingly, outdoor geodesic dome structures can replicate dark and hot conditions through their materiality, and therefore aid mycelial growth and plastic decomposition within them, with minimal risk of failure. Figure 1.3 below shows a "very strong, lightweight, easy to assemble/disassemble, and aesthetically pleasing" dome, designed to replicate greenhouse conditions (*Geodesic Bubble Dome FAQ,* 2022).

Fig. *1.3* "The Climatron geodesic dome, Missouri Botanical Garden, St. Louis." (cited from *Encyclopaedia Britannica*)

Unlike greenhouse geodesic domes, customized domes for mycelium decomposition should obtain black colours to absorb heat from the sun to create warm internal conditions. The external panels can be transparent and highly affordable PV film, whereas the internal surfaces covered with dark films will prevent brightness from entering the structure. In addition, it's important to consider that the dome is self-sustaining once assembled; the warm and dark conditions are a result of the materials interacting with the sun's chemical energy. The dome has the potential to become an extension to landfills or become facilities that biodegrade non-recyclable plastic. Overall, the geodesic domes exemplify how biotechnology can be creatively applied in myriads of disciplines, including architecture and structures, to maximize efficiency and intervention points when tackling plastic pollution.

1.1.2 Fungi growing packaging with plastic properties

Contradictorily to decomposition and breaking down matter, fungi are also capable of the opposite: the growth of solid mycelium structures. *Ecovative Design*, a biotech company which designs and grows sustainable materials directly from nature, utilizes mycelia from oyster mushrooms and agricultural waste to bio-fabricate packaging that can replace Styrofoam and other plastics (*MycoComposite*, 2022). *Ecovative Design* prepares mixtures of agricultural and mycelium from oyster mushrooms inside molds containing the desired shape and size and are left to grow into a solid block under the right conditions over the course of a week (*MycoComposite*, 2022). The resulting material is durable, lightweight, flame-resistant, and most importantly biodegradable, as seen below.

Fig. *1.4* Mushroom Packaging (cited from *MycoComposite*)

Analogous to the phrase "Kill two birds with one stone," oyster mushrooms can simultaneously decompose plastic pollution and bio-fabricate plastic-like packaging. According to the results from the previously mentioned *Fungi Mutarium* experiment, the agricultural waste could be substituted with plastic pollution. Overall, although oyster mushrooms could not thrive in a landfill environment as intended, their abilities could be capitalized on to manufacture biodegradable packaging, while eliminating pre-existing plastic pollution at the same time.

Another clever utilization of mycelium was found at the exhibition *Waste Age: What can design do?* at the *Design Museum* in London, which displayed a 3-D printed mycelium structure called *Tree Column – Using waste to build* by *Blast*.

Fig. *1.5* ‘Tree Column _ No1 – Using Waste to Build’ (Blast, 2021)

The column is made from discarded takeaway paper coffee cups, which have been digested by mycelium. The mycelium was then converted into a biological paste to be 3-D printed. Unlike the molding technique from *Ecovative Design*’s example, 3-D printer technology is capable of intricate detail and a myriad of designs and scales. Although the *Tree Column* was intended to transform waste into construction materials, the same biotechnology could be applied for 3-D printed packaging.

In addition, the *Tree Column* represents an important circular economy principle: the repurposing of pre-existing, standard machines (e.g., 3-D printer) through the innovation of materials (e.g., biological paste). Manufacturers often struggle to reach sustainability goals for reasons including in-house expertise, and time, costs and resources associated with the research and development of new manufacturing methods. Instead of inventing methods that require changes in both machinery and materiality, manufacturers can focus on simply repurposing the machinery. By innovating a new sustainable material to be malleable in similar ways to its conventional counterpart, the machines can work with alternative materials. *Amcor R&D*, a pharmaceutical packaging company, operates existing blister pack machines optimized to work with PVC (which is a stiff material) which have been standard for over 60 years, to also work with polyolefin materials (Gore-Langton, 2021). Unlike PVC, polyolefin is highly recyclable and releases significantly less contaminants in the environment; resultingly, this innovation brought blister packs one step closer to the circular economy of plastics (Gore-Langton, 2021). The eco-innovation concept of repurposing standard machines appears to be a viable approach to sustainability in manufacturing.

Overall, mycelium is a unique, natural biological process that can break down and build materials associated with the food packaging industry. More research is required regarding mycelial plastic degradation; nevertheless, bio-fabrication of mycelium packaging has been experimented with immensely and applied in real life to a greater extent. Mycelium can simultaneously eliminate and replace problematic plastic, and thus plays important roles in the circular economy of plastics.

1.2 Plastic packaging alternative via Biodegradable 'Plastic'

Efficient transportation, protection, preservation and safety of food deem plastic as the "ideal" packaging material, according to the British Plastic Federation (*Why Do We Need Plastic Packaging?*, 2021). Without plastic packaging to serve all those needs, "it becomes very difficult to transport and utilize a wide range of products people rely on daily" (*Why Do We Need Plastic Packaging?*, 2021). Since the recycling infrastructure is flawed, 'Bio-Based Food Contact Materials' (BBFCM's) are being developed to provide a replacement for oil-derived plastics, due to their ability mimic the properties of common packaging plastics such as Polyethylene terephthalate (PET) or Polyethylene plastic (PE).

1.2.1 Agri-food Packaging

Graham Bonwick, an applied biology professor at the University of Chester with expertise in food safety, environmental quality, and the circular bioeconomy, argues that "sometimes we just don't need the performance that those materials [plastic] actually give us" (Appendix A, 2021). For instance, plastic-based cling-film that won't biodegrade for decades is not needed for the preservation of products that will be consumed in a couple days. Bonwick claims that bio-packaging made from agri-food waste (agricultural and food waste) can replace plastic for short shelf-life products while meeting the modern needs of the food industry, and without contaminating the environment with microplastics (Appendix A, 2021).

Bonwick is also the director of *AgriFoodX Limited*, a company that conducts research and experiments to develop natural sciences and engineering whose mission is to "support innovation in the food supply chain within the context of a circular bioeconomy" (*Turning Waste into Wealth*, n.d.). The company cleverly capitalizes on agri-food waste, with over 100 million tons generated each year, into a valuable resource for biodegradable packaging (*Projects - Green Solutions for a Blue Planet*, n.d.) . The waste is a source of high value chemicals which can be used to create sustainable, bioplastic packaging. Fig. 1.6 below displays flexible films developed by AgriFoodX, made of leftover materials from the brewing and distilling processes and apple pomace, a by-product from when apples are pressed to obtain apple juice (Appendix A, 2021).

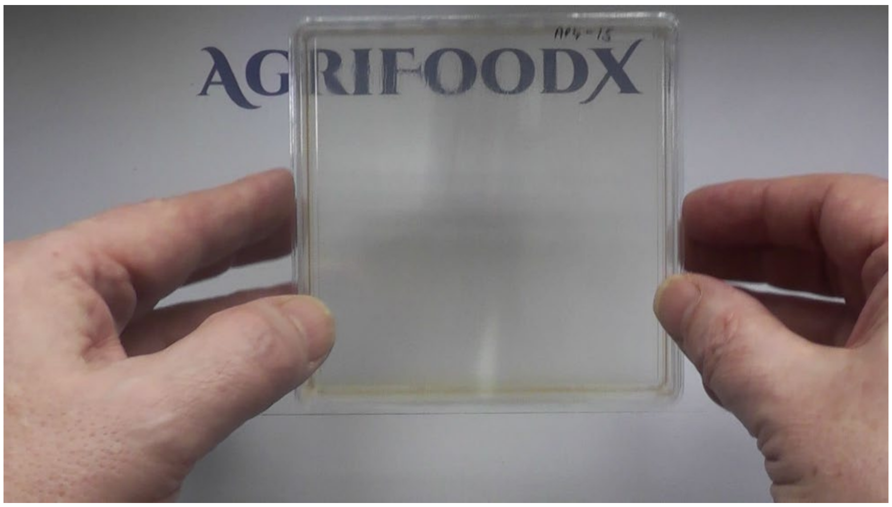


Fig. *1.6* Biodegradable flexible film (cited from *AgriFoodX*)

Interestingly, according to Bonwick, the farmers stopped donating and instead began to sell their apple pomace, indicating a mindset switch from 'waste' to an 'unused commodity' with value. Resultingly, AgriFoodX's demand for agri-food waste provided additional sources of revenue for farmers and stimulated economic activity. According to Bonwick, "as soon as you start wanting someone materials, even if they were considered waste and they were trying to pay to dispose of them, suddenly they realize there's a potential market there, and then the price starts through" (Appendix A, 2021).

In closing, the mindset switch is crucial for the development of a circular bioeconomy, that will encourage the diversion of food waste from landfills, generate jobs, and create physically and financially sustainable food packaging. Like *Ecovative Design*'s mycopackaging mentioned in section 1.1.2, *AgriFoodX'*s bio-based packaging reduces carbon emissions, is biodegradable, but most importantly redirects food and agricultural waste from the environment, into a valuable resource (*Turning Waste into Wealth*, n.d.). In *AgriFoodX*'s and *Ecovative*'s biotechnological examples, their systems cleverly capitalize on pre-existing resources from one issue (food waste) and redirecting them towards the solution of another issue (plastic packaging waste) - it works in harmony with society and nature.

1.3 Evaluation on biodegradable packaging sustainability

This section will argue that despite the biological origin of bioplastics, they face comparable end-of-life issues to oil-derived plastics. A survey on citizen attitudes and behaviors relating to food waste and plastic packaging by *WRAP* reveals that consumers have positive attitudes towards biodegradable and compostable packaging (Incpen & Wrap, 2019). For example, statistics demonstrated that 17% of consumers believe "making all food packaging biodegradable or compostable" is a better hypothetical approach to alleviate the negative impacts of food packaging than making "all food packaging 100% recyclable" (Incpen & Wrap, 2019). The citizens who favor 100% biodegradability over 100% recyclability of food packaging also indicate the need for convenient solutions to a modern throwaway culture as it requires more effort to recycle.

Fig. *1.7* "Thinking about how the negative impacts of food packaging could be addressed in the future. If you had to choose just one of the following approaches, which one would it be?" (cited from *WRAP*)

Contradictorily to the 17% of citizens that believe biodegradable products are more sustainable than their recyclable oil-based polymer counterparts, not all biodegradable packaging can be sustainably sent to the landfill according to *Eco to Go* (*Biodegradable vs Compostable Packaging*, 2019). Due to a landfill's compact conditions that lack oxygen and other special composting conditions (e.g., nitrogen, carbon, high temperature and moisture), biodegradable alternatives tend to not biodegrade and instead produce methane, a harmful greenhouse gas (Biodegradable vs Compostable Packaging, 2019). Until the packaging biodegrades, for a certain period, discarded biodegradable packaging negatively affects the environment amidst all other pollutants. For example, when biodegradable or compostable 'plastic' bags find their way into the ocean, they still cause sea-life to suffocate the same way as oil-derived plastic bags (Biodegradable vs Compostable Packaging, 2019). Since discarded biodegradable or compostable packaging needs further processing, biodegradable disposal-facilities equipped with ultraviolet (UV) lights and high temperatures were designed to speed up the decomposition process.

Systematically, biodegradable disposal-facilities are a solution that generates other problems. According to *Eco To Go* (*Biodegradable vs Compostable Packaging*, 2019), any packaging that is not biodegradable landfill packaging, ultimately requires its own waste stream to be sustainably processed. Analogous to recyclable plastic that requires cleaning, sorting and segregation to reach recycling facilities, biodegradable packaging requires similar if not more effort and awareness to reach the few and far biodegradable disposal-facilities. Therefore, despite the potential of biodegradable 'plastic,' it is not as sustainable as it seems when comparing it to recyclable plastic.

Overall, both types of packaging require streamlined recycling or disposal streams, which primarily rely on the consumer and proper material circulation. Therefore, the next chapter evaluates how the problematic recycling infrastructure can be streamlined through intelligent biotechnologies.

Chapter 2 – Innovation and Circulation of 'Necessary' Plastic Packaging

According to the *Ellen McArthur Foundation* (*Plastics And The Circular Economy*, n.d.), a circular economy for plastic requires the innovation of plastics to be recyclable, and the circulation of "all the plastic items we use to keep them in the economy and out of the environment." The first requirement is well under way: according to *Recycle Now* (*What to Do with Packaging (Food)*, n.d.), England's national recycling campaign, "most packaging is recyclable." Nevertheless, the issues lie on the recycling infrastructure, which is responsible for the collection, separation and sorting of the recyclables in preparation for material circulation. For instance, according to a 2018 report from *Fera Science Limited* (*Bio-Based Materials For Use In Food Contact Applications*, 2019), households accounted for 525,000 tons of primarily fossil-based plastic packaging, of which only 32% were recycled.

Section 2.1 will systematically locate the flaws of the recycling infrastructure that cause recyclables to end up in the unsorted waste fractions. Section 2.2 will propose and evaluate biotechnological applications that can streamline the material circulation processes.

2.1 Flaws of the Recycling Infrastructure

According to a journal by *Nature Catalysis* (Wei et al., 2020) on biotechnological recycling, since landfills are no longer an applicable 'end-of-life' option for plastics in a circular economy, recycling of plastics has become a necessity for material circulation. The incineration of plastic waste tends to produce CO_2 emissions and lowers the quality of the reprocessed plastic (Wei et al., 2020). Alternatively, material circulation utilizes resources to their full potential and reduces CO_2 emissions (*Plastics And The Circular Economy*, n.d.). Unfortunately, the infrastructure of material circulation faces several issues, which will be addressed in a chronological order below.

2.1.1 Collection

Even if a package is recyclable, it does not mean it will be recycled. A survey conducted by *WRAP* on citizen attitudes and behaviours revealed that over half of UK consumers (59%), agree with the following quote: "I'm less concerned about packaging, including plastics, if my council collects it for recycling and it does get recycled" (*Citizens Attitudes & Behaviours Relating to Food Waste, Packaging and Plastic Packaging*, 2019). There is a need for reduced responsibility for consumers to encourage recycling. For example, packaging is more likely to be recycled (correctly) when the consumer is not responsible for the separation of materials. Unfortunately, common multi-stream recycling where materials must be segregated into four categories (e.g., plastic/metal, glass, paper, and food waste) requires more effort and responsibility from the consumer (*Supporting Evidence and Analysis - The Case for Greater Consistency in Household Recycling*, 2016). In addition, incentives including deposit-return schemes that aim to incentivize the consumer to return packaging to re-claim their deposit, tends to fail in the absence of "committed public behaviour" and awareness of the scheme itself (Hopewell et al., 2009). Even with kerbside collection of comingled recyclables (e.g., paper, glass, aluminium, plastic) which has proved to be successful, typically only 30-40% of post-consumer materials are recovered (Hopewell et al., 2009). There is a need for more incentives to increase collection rates.

2.1.2 "The Plastic Sorting Challenge"

For plastics to be recycled, they need to be sorted to a "high degree of purity"; in other words, plastics would be able to be re-used and retain their value (Mehta, 2020). Sorting is a crucial process in the recycling infrastructure, which currently faces issues like necessary manual sorting and monitoring. For example, at least seven different types of recyclable plastics as seen in figure 2.1, where each of them must be identified and segregated at the recycling facilities (RI Admin, 2021).

Fig. *2.1* "Countless different types of plastic" (cited from *binit*)

Without an efficient monitoring and sorting system, the recyclables end up in the unsorted waste fractions also known as 'residue,' which get sent to the landfill (RI Admin, 2021).

2.1.3 Black Plastic

Lastly, black/dark plastic that is used in food packaging to contrast colourful foods is highly problematic in the recycling industry and is considered as one of the worst materials to enter a recycling plant (RI Admin, 2021).

Fig. 2.2 “The Truth about Black Plastics” (cited from *VPIRG*)

Traditional automatic systems like NIR lasers that are used to sort plastic, are incapable of identifying black plastics as seen in figure 2.2, since they appear to be invisible (RI Admin, 2021). Resultingly, the unidentifiable plastic eventually reaches the end of the processing line and is labelled as ‘residue’; in other words, it is sorted in the non-recyclable section, which is then sent to a landfill (“Black Plastic: What’s the Problem?,” n.d.). Though technically recyclable, black plastics do not get recycled, even if the consumer disposes it in the correct recycling bin. Conclusively, there is a need for innovations in scanning technologies, that can sort black plastics.

2.2 Biotechnology for plastic waste recycling

The following biotechnological applications are evaluated on their ability to tackle the flaws associated with the recycling infrastructure including collection, segregation, and processing of plastics in recycling facilities.

2.2.1 Fluorescent markers and UV scanning technology

Intelligent food packaging with integrated fluorescent markers on the labels has been developed by *Nextek* (Kosior, 2020) from earth-based compounds and recycled fluorescent lamps, to streamline the sorting of plastic packaging. According to an article regarding *Nextek's* PRISM technology (Kosior, 2020), the fluorescent markers are like invisible barcodes for plastics, that can distinguish between "food-grade and nonfood-grade polymers, identify black plastics and tag full-length shrink-sleeves." While the mixed plastics are on the conveyor belt, a complementary scanning technology with UV lights reads the coded fluorescent labels and segregates the plastics into the recycling streams accordingly (Kosior, 2020). Due to this ingenious biotechnological application, all types of plastic including the 'unsortable' black plastics can be quickly and automatically separated, without human intervention. Another advantage is that labels can still be read regardless of their physical state (e.g., crumpled, flattened or dirty), which is especially common in post-consumer food items (Qin et al., 2021).

Fig. 2.3 "PRISM technology uses luminescent materials on labels to identify food-grade plastic containers during recycling sortation." (cited from *Plastics Today*)

The fluorescent marker biotechnology can also improve single-stream sorting and recycling, which is associated with higher collection rates. Single-stream is the opposite of multi-stream recycling: it is "simply a single bin/cart or collection of all recyclables that requires zero sorting from consumers and businesses" (The Pros and Cons of Single Stream Recycling, 2021). Unlike multi-stream recycling, in single-stream recycling the responsibility is shifted from the consumer to the waste handlers in the recycling facilities, which incentivizes the consumers to recycle more. The ultraviolet scanning technology can tackle common issues associated with single-stream sorting, such as the reliance on human intervention to maintain purity levels (*The Pros and Cons of Single Stream Recycling*, 2021). Alternatively, the fluorescent markers can automatically remove non-recyclables and separate recyclables, which automates the conventionally complex single-stream sorting facilities. Resultingly, unlike multi-stream recycling, more consumers can benefit from the convenience of single-stream recycling, while waste handlers can benefit from the increased collection rates.

Overall, the fluorescent markers and scanning technology offer unique benefits in recycling. Despite the evident improvements in sorting plastics (including black plastic), the biotechnology also increases collection rates. The fluorescent markers revolutionized automatic sorting at a high speed and have the potential to bring plastic packaging into the circular economy.

2.2.2 Biotechnological Valorisation

When plastics are recycled, a significant conversion takes place called valorization: polymers are transformed into monomers, which can be used to make new plastic of different forms (Wei et al., 2020). Currently, the recycling industry uses mechanical and chemical methods for valorization, and therefore biotechnological strategies have been consistently overlooked (Wei et al., 2020) . However, according to the article *Biotechnological Solutions for Degradation and Recycling of Plastics* published by the University of Greifswald, modern biotechnology has the potential to contribute to end-of-use recycling of plastics by using enzymes or other derivatives from microorganisms to convert polymers into monomers.

According to a report called *Biotechnology of Plastic Waste Degradation, Recycling, and Valorization* (Qin et al., 2021), unlike low-grade recycled plastic (downcycling), valorization produces value-added products (upcycling). In other words, valorization utilizes materials to their full potential, which is a main priority in the circular economy (*Plastics And The Circular Economy,* n.d.). The report states that derivatives from fungi and bacteria "exhibit excellent hydrolytic activity in converting PET into two environmentally friendly monomers," and that they would "marvellously assist in accomplishing a circular economy of PET" (Qin et al., 2021). Although valorization through biological catalysers contains circular economy principles, the biotechnology is still in its early stages of development.

Conclusively, biotechnological applications can streamline the recycling infrastructure, and tackle common issues associated with collection, segregation, and processing of recyclable plastic. Material circulation for plastic packaging is essential to continue using plastic sustainably, which contributes to the prevention of food loss. This leads to the next chapter, which fixates on tackling plastic pollution and food loss at the hands of the consumer, due to problematic packaging attributes.

Chapter 3 – Innovation of Packaging Attributes via Active Packaging

Chapter three evaluates how bio-nanotechnological packaging attributes can improve user experience and help alleviate the negative effects of *indirect* environmental impacts (such as food loss & lack of recycling). Consumer hesitancies will also be evaluated as barriers to the commercialization of nano-food and nano-packaging.

Section 3.1 evaluates to what extent packaging attributes affect user experience, and ultimately influence food loss, recycling, and cleaning of food packaging. Section 3.2 evaluates active packaging attributes on their ability to prevent food loss and prompt consumers to properly dispose their packaging into the circular economy of plastics. Lastly, section 3.3 analyses consumer perception on the new domain of bio-nanotechnologies on food or food packaging.

3.1 Journal of Cleaner Production - “An environmental comparison of two packaging alternatives”

A paper by the *Journal of Cleaner Production* evaluates how indirect environmental impacts of packaging are dependent on consumer behavior (Wikström et al., 2016). Two packaging alternatives of 500 grams of minced meat are compared: a tube (left) and a tray (right).

Fig. *3.1* ‘The Packages’ (cited from *The Journal of Cleaner Production*)

Considering the direct environmental factors, the tube is more environmentally friendly than the tray due to the production of the packaging material and the end-of-life treatment (post-consumer). Nevertheless, when indirect effects and user behavior are also considered, the tray is the better alternative due to “higher recycling rates and more importantly less food waste” (Wikström et al., 2016). The authors argue that a full-cycle analysis must include both direct and indirect environmental impacts when a judgement about the package’s sustainability is made (Wikström et al., 2016). The two packages were compared by packaging attributes, including: mass, food preservation, and how easy it is to empty, clean, separate and fold the package for recycling.

Attribute	*Minced meat- Tray*	*Minced meat – tube*
Easy to empty	Yes, no meat left on packaging surface.	No, some meat sticks to the plastic.
Easy to clean	Yes, just rinsing.	Very difficult due to packaging design. The meat may be looked upon as a bit disgusting to handle.
Easy to separate into different fractions	Not needed.	No. The metal clips can only be separated from the plastic by using a pair of scissors.
Easy to fold	No, takes some space.	Yes
Information on how to sort	Yes	Yes, but difficult to do, see "Easy to separate".
Preserve content	9 days from packaging date to expiry date.	16 days from packaging date to expiry date.
Mass	Moderate to high.	Very low.

Fig. *3.2* "Packaging attributes that affect behavior" (cited from *The Journal of Cleaner Production*)

According to figure 3.2, the tube is less likely to be recycled than the tray. According to the *Journal of Cleaner Production* (Wikström et al., 2016) , the tube's low mass tends to appear of low value by most consumers. Thus, people feel the necessity to "clean it if it is recycled for its material value, and sense that cleaning is a bit difficult" (Wikström et al., 2016). Furthermore, psychology with product packaging indicates that the material of a package tends to perceive the quality of the item it contains. For instance, although "plastic offers durability and ease of use" (*Glass vs Plastic: 7 Factors to Consider for Packaging Your Product*, n.d.), expensive and 'highly valuable' champagne is never packaged in plastic bottles, only glass: Psychologically, luxury feels heavy. For similar reasons, the tube's soft plastic is assumed to be of lower value than the tray's hard plastic and therefore is less likely to be recycled.

In addition, the consumer needs to segregate the plastic from the metal clips to recycle the tube; thus, the segregation is difficult without any sharp tools, deeming it time-consuming and difficult (Wikström et al., 2016). The tray, however, is a mono-material (consists of only one material) and can be recycled in its original state.

Most importantly, the tube proved to be less environmentally friendly than the tray, primarily due to the food waste it generates. According to the report, an average of 10 grams of meat sticks to the inner surface of the tube (near the two metal clips) and can be difficult to empty once opening (Wikström et al., 2016). Regardless of the impact of the packaging itself, the tube is the significantly worse environmental alternative due to the food loss.

Conclusively, food waste always "dominates over all other factors – packaging composition, recycling rates and cleaning" (Wikström et al., 2016). Although indirect environmental impacts which are "driven by user behavior, attitudes, and social norms are difficult to determine quantitatively," the authors argue the that they're even more important than the direct environmental impacts (Wikström et al., 2016). Therefore, the next section evaluates how active packaging, a bio-nanotechnological application used in smart packaging for food, can alleviate the indirect environmental impacts of packaging that primarily lead to food loss.

3.2 Active Packaging Attributes

Active packaging is a bio-nanotechnology: the use of biological small materials that measure changes in the environmental conditions (Appendix A, 2021). For example, in COVID-19 rapid tests, any present antibodies will react with nano-gold particles formed into a line, which reveal a purple 'Test' line as it interacts with light, indicating the person is positive (Appendix A, 2021). The rapid test is a chemical reaction that only occurs when the antibodies are present. The same type of bio-nanotechnology is applied in active functional packaging to create 'smart packaging' that can create customary use-by dates for the item it carries (Mustafa & Andreescu, 2020).

According to *WRAP*, one of the world's leading sustainability charities, suggests that 'use-by' dates on packaging are responsible for unnecessary food loss (Sawa, 2019). Although certain items including milk remain of good quality after their use-by dates, 490 million pints on milk are wasted annually in the UK (Jolly, 2022). According to an article by *The Guardian* (2022) the supermarket chain *Morrisons* will eliminate use-by dates on 90% of its own brand milk packaging (by January 2022) to reduce food waste (Jolly, 2022). Instead of use-by dates, *Morrisons* recommends customers to sniff the milk to check its quality. Consequently, *Morrisons* has faced backlash over the elimination of use-by dates for exclusive behavior and discrimination "against those with impaired smell," (Walker, 2022). In addition, human error could unnecessarily make the consumer throw away good milk. This application is yet to happen and there is no data on the indirect environmental impacts from consumer behavior. Nevertheless, there is a need for accurate use-by information to reduce food loss, while optimizing customer satisfaction. Active packaging attributes are a proposed solution capable of satisfying both ends, as seen below (Gray, 2021).

3.2.1 Time-temperature Indicators

Smart labels and sensing technologies record and display information on the "freshness status of food by measuring environmental conditions inside the package" (Mustafa & Andreescu, 2020). Below is an image of time-temperature indicator (TTI), which changes color when microbial (bacterial) growth is detected inside the milk, indicating an expiration date or the mishandling of food in the supply chain (Zhang et al., 2013).

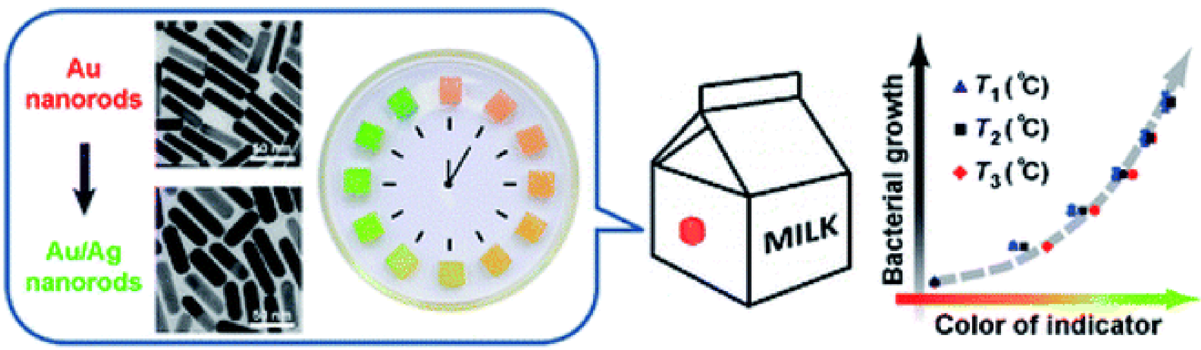


Fig. *3.3* "Time-Temperature indicator based on silver growth on gold nanorods creating a change in color related to microbial growth which is governed by time and temperature" (cited from *ACS Nano* 2013, 7, 5, 4561-4568)

The TTI's record the thermal history of the food over time and assess the growth rate of bacteria during the product's entire supply chain; the irreversible color change is a visual signal that the milk is no longer of good quality (Mustafa & Andreescu, 2020). TTIs' are highly unlikely to undergo a color change without the necessary environmental conditions and is considered a 'reliable indicator of product quality' (Zhang et al., 2013). The disadvantage of conventional use-by dates are the assumptions as they are not always accurate. Alternatively, active packaging including TTI's will react customary to the content it carries.

Contradictorily to the above, according to the interview with Bonwick who attended a packaging conference recently, TTI's were tested in Sainsbury's supermarkets and revealed some unexpected indirect environmental impacts (Appendix A, 2021). Consumers would buy chilled products and store them at the trunk of a car, which is relatively warm. The consumers tend to stop by other places before returning home and prolong the exposure of the packaging to warm conditions. By the time the consumer goes home and looks at the label, they notice that the TTI underwent a color change. Resultingly, the food gets thrown away under the impression it went bad.

Similarly to Bonwick's conference, a report on the consumer perceptions on TTI's also concluded that the reliability of the biotechnology was questioned in several EU countries, including Greece and Finlan (Pennanen et al., 2014) d. The report states that TTI's were considered useless since they cannot differentiate whether the product is indeed spoiled or if the product was just exposed to time and temperature (Pennanen et al., 2014). For instance, the warm conditions of the car which triggered the colour change in TTI's does not guarantee the food got spoiled. Ironically, the TTI's which were intended to prevent food loss, instead misinformed the consumers, and contributed to more food loss. According to the same study (Pennanen et al., 2014), The biotechnology has its limitations, but despite the results, "further research is needed regarding the development of actual TTI applications." More research and social experiments must be conducted to ensure they are tamperproof.

3.2.2 Ripeness Indicators

Although the parameters of time and temperature are easily tampered by consumer behavior and cannot evaluate the quality of food accurately in TTI's, currently developed ripeness indicators for fruits and vegetables do not face such limitations. The ripening indicators are tablets designed to measure ethylene – a gas that is released by some fruits and vegetables which causes them to ripen ("Ethylene in Fruits and Vegetables," n.d.). According to the journal article on nanotechnology-based approaches for food sensing and packaging applications, when certain fruits ripen, an excessive amount of ethylene is secreted (Mustafa & Andreescu, 2020). The ethylene levels are used as a "degradation marker to assess the quality and freshness of packaged food" (Mustafa & Andreescu, 2020). Below is an image of the tablets used to scavenge and measure ethylene in avocados, where "the colour of the ripeness indicator changes with the fruit ripening process" (Putri et al., 2019).

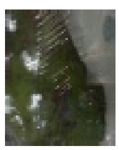
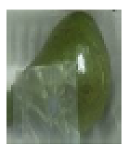
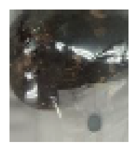
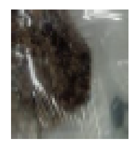
Days	6	7	8	9	10
°Hue	245.48	269.57	267.16	267.61	268.105
Indicator					
Application indicator					

Fig. *3.4* Image of avocado ethylene indicator changing color (cited from *IOP Conference Series: Earth and Environmental Science*)

Unlike the TTI's, the tablets are triggered by a gas directly linked to the process of ripening, deeming their nanomaterial function as highly reliable and accurate in the assessment of food quality in smart packaging (Putri et al., 2019). Nevertheless, the ripening indicators are strictly applicable to fruits and vegetables that secrete ethylene. The parameters would be different for non-sensitive ethylene fruits and vegetables, or meat and dairy, all depending on the gasses or chemicals released when those foods begin to spoil. Resultingly, each food category would require the development of their own indicators. Overall, nano-packaging has the potential to create customized expiration dates for its products, which has not been possible in the past.

3.3 Society Acceptance

Active nanomaterials have been developed into edible coating surfaces and "blobs" with antibacterial barriers and oxygen absorbers (Mustafa & Andreescu, 2020). Edible packaging outperforms single-use plastic performance, and simultaneously eliminates the need to clean, segregate or recycle. Despite those unique benefits, consumers are reluctant to accept products incorporating nanotechnologies, especially ones directly onto agri-food products.

Broad acceptance on nanotechnology is required for its successful implementation and commercialization; without it, the "potential economic and social benefits of nanotechnology may not be realized" (Giles et al., 2015). Below are examples of nano-food that despite their potential and safety, existing consumer hesitancies are interfering with their commercialization.

3.3.1 Edible "Blobs"

Oxygen-scavenger sachets (edible "blobs") made from seaweed were designed to replace conventional "single-use beverage bottles, cups and condiment sachets" (*Plastics And The Circular Economy*, n.d.). The condiment sachets by *Ooho* were tested in a trial involving ten restaurants, where 46,000 sauce single-use plastic sachets were avoided, suggesting that oxygen-scavenger technologies have great potential in food applications (*Plastics And The Circular Economy*, n.d.).

Fig. *3.5* “Notpla x Heinz Tomato Ketchup Sachet for the takeaway industry” (cited by *Notpla Sachets*)

According to a journal on *Comprehensive Reviews in Food Science and Food Safety* (Yildirim et al., 2017), the edible blobs are not accepted by European consumers, as they are “recognized as foreign bodies in food containers” and are inclined to accidentally break, leading to involuntary consumption or food loss (Yildirim et al., 2017). The sachets exemplify the various types of consumer concerns that can arise from packaging attributes, despite the obvious sustainable benefits the technology provides.

3.3.2 Edible Coatings

Bio-digestible and plant-derived coatings extend the shelf-life of fresh fruit and vegetables and are “Generally Recognized as Safe” (Ellen MacArthur Foundation, 2020a). The coatings have antimicrobial functions, with the “aim to preserve food items an prolong shelf-life by inhibiting microbial growth” (Mustafa & Andreescu, 2020). Below is an image that compares the shelf-life of red grapes packed in plastic wrap (left) versus chitosan film (middle and right).

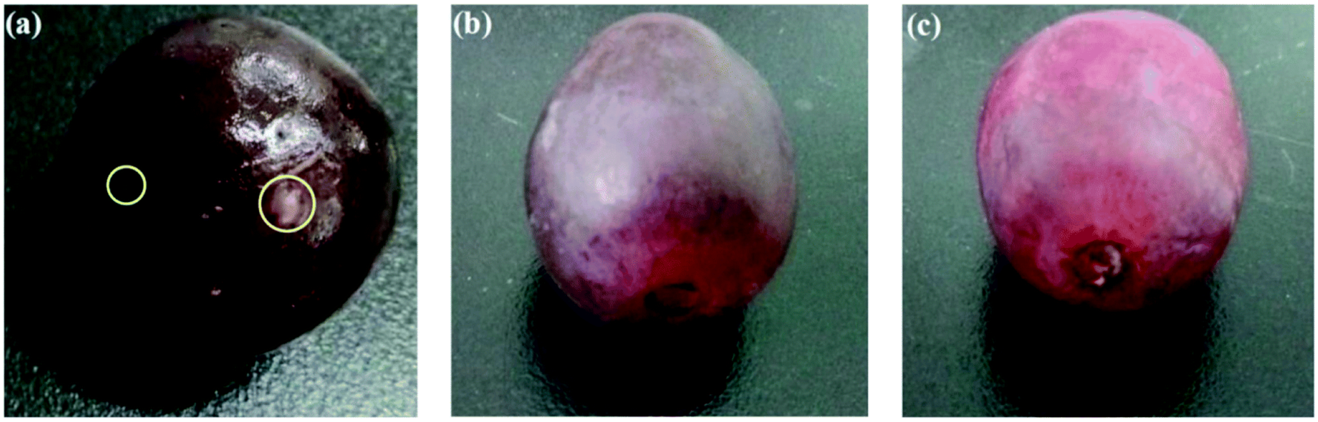


Fig. *3.6* “Extended shelf-life of red grape packed at 37 °C for 6 days in (a) plastic wrap; (b) chitosan film; (c) chitosan–TiO2 film” (cited from *RSC Advances*)

According to figure 3.6, the chitosan coatings performed even better under high temperatures than the conventional plastic wrap (Mustafa & Andreescu, 2020). In addition to the excellent preservation performance, the consumer has no responsibility to clean, segregate or recycle. On another note, edible packaging including edible coatings and “blobs” are a solution to wrap-rage, which is closely associated with plastic packaging that is hard to open such as clamshells, shrink films, and heat-sealed packs.

Fig. *3.7* Clamshell and shrink wrap packaging in the food industry (cited from *Mike’s Produce* and *Cucumber Growers Association*)

According to an article on clamshell packs (Smith, 2020), wrap-rage is the "constant source of frustration and even at times, a source of bodily injury" from packaging. For example, packaging costs the NHS twelve million dollars annually because of accidents that occur when people use sharp tools and weapons to open packaging (The University of Sheffield, 2003). Packaging that causes wrap-rage is also exclusive to older consumers who tend to struggle with applying force or leverage to grip and open certain packages (Parry, 2014). Package-less foods automatically eliminate the packaging attributes that tend to frustrate and injure consumers. Overall, nano-foods are a product of the evolving food market, with demands for healthier, higher-quality foods, long shelf-lives, and the need for convenient opening and disposing patterns.

Despite the unique benefits of nano-foods, consumers do not accept them primarily due to doubts regarding the safety of the coating, and that "technologies that are applied to food products should not be 'invisible' to consumers" (Cheuk-Hang Wan et al., 2007). The consumers tend to assume that the coatings influence the sensory qualities of the food (taste and odor), although studies reveal that coatings have similar "fresh aroma and improved appearance" on the fruit and vegetables (Brown & Kuzma, 2013). Lastly, according to research regarding *Understanding Consumer Attitudes on Edible Films and Coatings* (Cheuk-Hang Wan et al., 2007), cost is another concern regarding edible food coatings. Typically, consumers buy the least expensive option (uncoated products). However, the participants suggested that if they were aware that the coated products are "value-added products" through descriptive labelling, they would pay higher price if the benefits were obvious (Cheuk-Hang Wan et al., 2007). Conclusively, consumer assumptions, misinformation and lack of information are the current drivers of reluctancy in nano-foods. Familiarizing the consumer about nanotechnology is highly important for its commercialization in the food industry.

Overall, it is evident that the consumer is a recurring factor that needs to be taken into consideration when innovating and commercializing food packaging. Indirect environmental effects usually occur due to consumer reactions to ineffective packaging attributes, which ultimately lead to lack of recycling and increased food loss. Although nano-packaging and nano-food is intended to improve packaging attributes and reduce indirect environmental impacts, the evaluation revealed that the biotechnologies face their own share of misunderstandings with the consumers. With further research, development and raise of awareness regarding nanotechnology, nano-food and nano-packaging have the potential to revolutionize packaging by encouraging recycling, reducing plastic use and food loss altogether.

Summary and Conclusion

In conclusion, biotechnological applications have the potential to revolutionize the food packaging industry by applying circular economy principles to plastics. The previous chapters have evaluated how biotechnologies can eliminate/replace problematic plastic packaging, streamline plastic recycling, and improve consumer user experience.

Plastic technology has been around in the packaging industry for a long time, which has resulted in the establishment of vast manufacturing and distribution capabilities. Consequently, new technologies (including and not limited to biotechnologies) are facing resistance from the existing plastic-dominant industry and are collectively up against vested interests. Regardless of scientific knowledge and finances in terms of creating and fully developing biotechnological applications in the food packaging market, the nanotechnologies need to move into the mainstream, comparatively to plastic, through society acceptance and consumer convenience.

Despite the driving forces of unnecessary and problematic plastic use, oppositional legal obligations (bans and fees) against single-use plastic require manufacturers to adapt and innovate globally. For instance, multiple states in the USA and certain countries in the EU have enforced bans on single-use plastics. In addition, the lack of landfill space is another restriction that is forcing certain regions to circulate their materials out of necessity. For instance, since the USA is exceptionally large geographically, landfill sites are easy to find and very cheap. The UK, however, is densely populated and is an island; it is becoming expensive and more difficult to use landfill space (Appendix A, 2021). Resultingly, it is to everyone's benefit, environmentally, socially, and financially, to improve recycling schemes and material circulation.

Lastly, although this dissertation is fixated on biotechnological innovations in the food packaging market, their successful commercialization will inevitably influence bio-innovation in other packaging markets too. Considering food packaging must comply under some of the most restrictive requirements such as sterilization, protection, and preservation of contents (like pharmaceutical packaging), lower standard non-ingestible product packaging has even less obligations to adhere to. Thus, biotechnological advancements in food packaging would ultimately satisfy the demands of packaging across other industries.

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Appendices

Appendix A:

Thematic Analysis on Semi-Structured Interview with Graham Bonwick

Colour-code Key:

Biotechnology
Europe VS. USA
Existing Industry
Recycling Infrastructure
Incentive VS. Penalty
Consumer Behaviour
Further research

00:00:04.210 --> 00:00:34.550

Graham Bonwick

OK, so uh, my name is Graham Bonwick. My profession is primarily a researcher and formally Electra. I was formerly a professor of applied biology. I still retain the title as a personal chair. Uhm, I'm currently working in industry. I co-founded a business just over two years ago, which focuses on our recovery of sustainable materials and high value chemicals from agricultural and food waste.

00:00:36.720 --> 00:00:39.140

Marianna Olivia Lordou (Student)

Sounds very interesting.

00:00:39.830 --> 00:00:40.310

Graham Bonwick

It is.

00:00:39.870 --> 00:00:49.990

Marianna Olivia Lordou (Student)

What is the Institute of Agrifood Research and Innovation? What is your role in the company?

00:00:50.500 --> 00:01:48.770

Graham Bonwick

OK, so the Institute for Agrifood Research and Innovation was or is a part of Newcastle University, which was my former employer. Uh, and so the Institute seeks to sort of encourage academic and industrial partnership so the food and so Ferrer sciences. It's properly called Farrah Science Limited, was formally the Food and Environment Research Agency, but became privatized and is now a division of the capture group. So essentially, as an academic industrial partnership, and it was to encouraged that academics and industrialists to work together.

00:01:50.160 --> 00:02:02.700

Marianna Olivia Lordou (Student)

Uh, so like you mentioned, you're a professor of applied biology. I assume that is the action of applying biology to solve real world problems and creating byproducts.

00:02:01.330 --> 00:02:03.710

Graham Bonwick

Yes, that's correct, yeah.

00:02:04.100 --> 00:02:12.020

Marianna Olivia Lordou (Student)

So do you find ways to utilize food waste or food packaging waste? Just to clarify.

00:02:11.570 --> 00:03:45.700

Graham Bonwick

We're focused on exploiting agricultural and food waste, which can be used for creating packaging as well as other things. So I mean, formally, I established an industrial academic group called Future Pack, which was designed to try and encourage research in sustainable packaging and also to try and encourage training and as a result of that activity the first apprenticeship in packaging technology was developed. But also encouraged work between universities and industry to try and develop more sustainable packaging. So that future pack a group, it was just a loose collection. We organized a range of meetings over several years to try and discuss how to make packaging more sustainable in particular. Ah, that's no longer functioning. We have actually set up a thing called future pack CIC, a community-interest company to try and sort of progress more of the sort of public education side. But unfortunately, because of the pandemic, our attempts to interact and engage with the public have been somewhat put back. So future pack as an entity still exists with an overall aim of encouraging awareness and sustainable packaging.

Theme/s: Biotechnology → Agri-Food Packaging
- Agricultural & Food waste is utilized to create bio-packaging.
- Investigate Future Pack's mission and examples of agri-food packaging.

00:03:49.700 --> 00:04:00.620

Marianna Olivia Lordou (Student)

And do you have any actual prototypes of those packages and the actual sustainable material, or is it research?

00:03:59.170 --> 00:04:06.820

Graham Bonwick

Uh, yeah. So I work now for agrifood X.

00:04:08.700 --> 00:04:51.180

Graham Bonwick

As a business, we've developed materials from waste that can be used to create sustainable packaging. So they're at the prototype stage. So we've created, for example, flexible films which could be used in a range of applications. So it's very early. It's fairly early days, but yes, in its prototype stage. And the other thing that we're doing at the moment is trying to come up with a prototype to a replacement for things like food trays. And punnets for fruits. Yeah, getting created primarily from waste but also based on biodegradable polymers.

Theme/s: Biotechnology → Bio-alternatives
- Flexible films, food trays and punnets made from biodegradable polymers found in agri-food waste.
- Replacement of conventional plastic.

00:04:44.620 --> 00:05:00.290

Marianna Olivia Lordou (Student)

And like the type of waste you use, is that from farms or woodlands? What are those byproducts?

00:04:59.220 --> 00:05:30.810

Graham Bonwick

So the main wastes we've been looking at in recent times have been things like Apple pomace, which is the material leftover when you press it to obtain apple juice. Uh, so Apple pomace is one material, the other one, which is available in very large quantities throughout the UK, is Brewers spent grain and also distillers spent grain, more so in Scotland. And so these are the leftover materials from the brewing and distilling processes.

Theme/s: Biotechnology → By-products

- Byproducts include apple pomace (leftover material when pressing juice), spent grain from brewery and distillery processes.

Marianna Olivia Lordou (Student)

And I assume, you have infinite supply of those and actually get them for free, right?

00:05:35.050 --> 00:06:09.970

Graham Bonwick

Well, that's that's a very interesting question. As soon as you start wanting someone materials, even if they were considered waste and they were trying to pay to dispose of them, suddenly they realize there's a potential market there, and then the price starts through. It becomes. Yeah. So in a way, it's quite good because I'm very keen on this idea of stopping people talking about things as waste and actually realizing they're just an unused commodity. There are resource waiting to be utilized, and that means if we give them value and people will actually look after them and try and figure out how to best make use of them.

Theme/s: Incentive/Penalty & Consumer Behavior

- Attitude Change: Waste becomes a valuable resource when there's demand for it.
- When waste is seen as an unused commodity, economic activity is stimulated.

00:06:22.390 --> 00:06:44.300

Marianna Olivia Lordou (Student)

So what are the benefits and challenges when applying sciences into the real world? Like, would it be a lack of knowledge or just lack of general awareness? I mean, what's what would you say is holding it back and what is like the potential for it? If it does like liftoff well and this collectively sustainable?

00:06:44.670 --> 00:09:01.670

Graham Bonwick

OK, that that's a that's a big question. A lot of a lot of answers. So I guess that that that the answer range from things like scientific problems. I mean, the issue is actually obtaining and developing these materials, so they perform in a way that's expected. So, for example, plastics, oil-based plastics have been around for some time, they work very well. Uh, so the challenge is to come up with materials that perform as well, and that that is quite difficult. But there's a reason why we use plastics oil-based plastics. It's because they're very good. But there's a scientific challenge in terms of creating materials from sort of bio resources that perform as just as well, but I guess also we can go to other areas. We can say well, for example, there's there's economic problems: trying to obtain the finance to develop these materials is difficult, certainly as a start up business. And there's also political or other factors. Economic factors, I guess. Maybe a mix. The current plastic industry based on the use of oil is very powerful. The the oil lobby. The plastics industry is exceptionally powerful. They have a well-established market and there's a great deal of investment taking place to establish the manufacturing distribution capabilities. So there's a resistance from existing industry which is concerning, but we know we're kind of up against some very sort of vested interests. So yeah, there's challenges from many directions. I think it's easiest thing to say, I don't think it's so much of a challenge getting consumers to understand and accept the need for new materials. I think there's a great deal of information in the media now. Several years ago, before there was this sort of awareness of plastic in the environment, I think the general consumer was fairly unaware there was a problem, but in a way it's I think it's very good. Fortunately, the media has backed this and brought it to the public's attention, which is excellent.

Theme/s: Pre-Existing Industry & Consumer Behavior

- Resistance from the existing plastic-dominant industry makes it challenging to innovate alternative technologies. Look further into why plastic is *needed* in food packaging.
- Consumers broad acceptance to new materials should not be an issue since consumers are fairly aware of the effects of plastic in the environment. Investigate further consumer acceptance on specific biotechnologies.

00:09:02.440 --> 00:09:47.320

Marianna Olivia Lordou (Student)

Yeah, there's a definite improvement, but I have a small counter argument to that and I want to hear your opinion on it. From personal experience, I’ve came across people who simply don't care about being sustainable. I think it's either a motive of trending behavior or money that incentivizes people, like in America you’d get paid by returning a can, let's say, and that incentive puts that material back into the re-manufacturing process. But like in the UK, you get penalized when you don't recycle materials by getting fined. I feel like like there, there are many political ways to look at this.

00:09:46.600 --> 00:10:58.930

Graham Bonwick

No, I I think you're absolutely right that there's there's different attitudes, and there will be people who cannot see why they should perhaps change what they do. I think it's our job to inform people so they can make the right decisions. We you know we are in a climate crisis which is predominantly based on the exploitation of fossil carbon resources and that includes materials derived from those such as plastics. So I think it's all part of the a large picture we have to, though perhaps break it down and make it easy to understand and try and persuade people to make changes, even if they're very small ones. Uh, we can incentivize people, sure, yes, we can encourage people to return used packaging, for example, such as deposit return schemes, which I think is again just part of the picture. We should try a range of activities because one of those may appeal to that sceptical person and get them to do something. So I think we need to put apply a range of incentives.

Theme/s: Consumer Behavior & Incentive/Penalty & Europe VS. USA

- People need to be incentivized to recycle and thus encourage the circulation of materials and resources.
- Deposit return schemes which are common in America reward money to the consumers when they return packaging. In the UK, however, penalization is more common than reward schemes. For example, In London, garbage trucks limit their visits to once every 2 weeks, whereas recycling bins are emptied once a week.

00:10:42.550 --> 00:11:20.540

Marianna Olivia Lordou (Student)

Do you think it's feasible to rely or trust the consumer to do their part in like a circular economy by returning the material back into the process? Or do you think companies should just expect people to throw it away and therefore just aim making something biodegradable because it will probably be thrown out instead.

00:11:21.300 --> 00:12:13.540

Graham Bonwick

Again, I think there's going to be a range of behaviors. There will be. Some consumers are very conscientious, very well aware and will make take steps to do things such as return and recycle materials. But there will be many people who want the convenience that they used to have just simply throwing away and discarding waste materials. And if that's the case, then we have to try and work with that. We have to understand consumer behavior. We can try and sort of nudge peoples behavior to change it slightly, but at the same time I think we have to appreciate how people tend to live and work. And we've all got used unfortunately to this sort of throwaway society. So I think we have to kind of live with that. So that means then we have to help the consumer, so if they are throwing things away at least help try and persuade them to segregate those materials in the home or in the workplace. That would really help.

Theme/s: Consumer Behavior → Consumer Psychology

- Before designing packages, we need to understand how people live, work, think and react to certain attributes. The attributes should intuitively guide the consumer to recycle and not throw away food.
- Explore biotechnological attributes, and if they can improve recycling rates and prevent food loss.

00:12:15.040 --> 00:12:49.300

Marianna Olivia Lordou (Student)

Another similar thought that came to my mind yesterday about the big Amazon packages and cardboard boxes. I feel like it's very self-implied that they should be recycled because first of all, like they're too big and they would waste too much space in your regular trash can. Cardboard is also easily identifiable as a recyclable material, and hence more people are likely to recycle. Unfortunately, I think this is a bit different with food packaging because you're more likely to just bin it. For example, I know like my flatmate she buys chicken a lot. She always has to wash the package before recycling it which is a task, and it's not self-implied if the plastic is recyclable or not. So, do you think user experience matters a lot?

00:13:03.950 --> 00:13:24.660

Graham Bonwick

Absolutely I. I think packaging should be designed with the consumer in mind. It [packaging] should be designed also to take into account how it's going to be processed at the end of its life so process for full recyclability or circularities essential.

Theme/s: Recycling Infrastructure → End-of-life Processes - A package's sustainability depends on what happens to it at its end-of-life. - Just because something is recyclable, does not mean it will be recycled. Recycling primarily relies on the consumer to dispose of the package correctly

00:13:23.930 --> 00:13:39.180

Marianna Olivia Lordou (Student)

Separation of materials is another issue. Label it's huge issue because you have the plastic that can be recycled because of the label that's stuck on it. A lot of packaging is gets rejected at the recycling facility because of that.

00:13:26.620 --> 00:15:26.720

Graham Bonwick

Yeah, absolutely. So complex packaging. We've got mixed materials which can't be separated easily. Surely those should be redesigned so they can be separated more easily, either by the consumer or when they're processed by a waste handler. So yeah, design for end of life is essential. I'm a bit skeptical. I don't think consumers understand or read recycling labeling on packaging. Yeah, and who knows what all the different symbols and numbers mean. So people just want to throw it in the bin 'cause that's the least effort, you know it's the easiest route, so if that's the way that people behave and then we need to kind of roll with that and design for that eventuality. Yeah, so design for end of life. Very important, not just designed to carry out its normal function. Design it so the components can be easily separated and identified if not by the consumer, then at least by the waste processor. So that means then for example do materials need to have embedded markers so that it can be identified easily and separated so by the various sorts of scanning technologies that are now exist. So I'm embedding say fluorescent or other markers within the materials would be very useful to segregation. Yeah, I think it's you know we have to tackle this on all fronts, you know, try and encourage consumers to handle their waste appropriately to segregate into the right waste streams and make it easy for the waste handlers to segregate as well.

Theme/s: Recycling Infrastructure & Consumer Behavior & Biotechnology

- The current recycling infrastructure is problematic because packaging is often made of at least two materials which need to be segregated to be recycled. For such packaging, the consumer or the waste handler has the responsibility to segregate the materials.
- Due to lack of information regarding recyclables on the labels, consumers get confused and give up on recycling. Some households with economic struggles may also not have the time and effort to recycle at all.
- The less responsibility to recycle, the better.
- Fluorescent markers and scanning technologies can streamline the segregation process of recycling. This could reduce the manual labor costs at recycling facilities.

00:15:29.140 --> 00:15:42.230

Marianna Olivia Lordou (Student)

Does innovation in sustainable packaging require interdisciplinary collaboration, like what would you say are the various roles and fields that are necessary for that development?

00:15:41.740 --> 00:17:08.740

Graham Bonwick

I actually think that packaging is an exceptionally interdisciplinary area. Uh, you have everything from material scientists who design develop the materials. You have, say graphic designers have a role sort of designing labels and information delivery. I think there's also a role for understanding consumer behavior. So you need behavioral scientists as an example. How do people interact with their packaging? And that will also guide a good design principles as well. Foods are for example with food packaging. You need food scientists to understand how the packaging performs. Does it meet specification? You need engineers to understand the mechanical performance of packaging materials. So yes, it packaging is a very ignored but an exceptionally interesting area I've having sort of been part of, and having designed packaging, training courses and also delivered them as well. Uh, it's not until you get involved in that you suddenly realize just how multidisciplinary packaging actually is. And yet it's such a big part of our lives, and it's a big part of the economy. it's hard to understand why it's so ignored, but particularly in this country (UK).

Theme/s: Consumer Behavior & Biotechnology

- Packaging design should consider the physical engineering and development, but also the consumer's UX. Graphic designers and behavioral scientists determine how consumers interact with packaging, and if the packaging attributes lead to food loss or lack of recycling.
- Packaging is widely ignored, despite its negative effects on the environment.

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Marianna Olivia Lordou (Student)

I think packaging takes up 28% of all solid waste. Packaging has that nature of being discarded within 10 minutes after its bought. So why would it be made of something non-biodegradable like plastic? In some case it's non-recyclable, like PVC for example.

00:17:31.420 --> 00:18:10.890

Graham Bonwick

No, true true. I often sort of think to myself that if some of these oil-based plastics were invented today in today's climate, and understanding, would we even bother to use them? But again, it's either. As I said, there's some excellent materials, it's just we need to make sure they're used and handled appropriately. So take the plastic PET an excellent material, particularly food packaging, but the key though, is to make sure it is fully collected and recycled as much as possible.

Theme/s: Recycling Infrastructure

- Plastics including and not limited to PET are excellent at what they do, but they are not handled appropriately (recycled).
- Recycling is a priority.

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Marianna Olivia Lordou (Student)

Yeah, 'cause PET is recyclable but I know in the states they barely collected and actually recycle it. It just ends up in landfills so I think it's a very poor infrastructure. That's the core problem. Sustainable alternatives exist. It's more about the infrastructure that would run the whole operation.

00:18:30.610 --> 00:18:44.040

Graham Bonwick

By my understanding was that in the United States, recycling rates are around about sort of 20% for certain materials, whereas IT equipment tools may reach in parts of Europe, may reach up to 90%, so it can be done. Uh, and I guess it depends on. You know, maybe we need certain incentives to make sure that these things happen. I mean, the United States has an exceptionally large country, so, but I presume finding landfill sites is very easy and cheap. Whereas in the more highly densely populated yeah sort of United Kingdom, it's a bit more of a challenge and went. We're running out of landfill space, so.

Theme/s: Incentive VS. Penalty & USA VS. UK

- Recycling rates are 20% (USA) vs. 90% (UK)
- Restrictions (e.g. lack of landfill space) are incentives that force us to 'get things done'
- Investigate France's legislations and bans on single-use plastic.

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Marianna Olivia Lordou (Student)

Yeah, it's those restrictions that make us act better and find alternatives we need.

00:19:14.330 --> 00:19:18.120

Graham Bonwick

So there's a role for legislation, isn't there? And and enforcement as well?

00:19:20.370 --> 00:19:32.900

Marianna Olivia Lordou (Student)

Uhm, so I'm going to move on to the bio technology point of view. I've noticed in your RSA profile you have an interest in Bionanotechnology is could you please define that?

00:19:36.350 --> 00:22:15.600

Graham Bonwick

So nanotechnologies this it's the the use of very small materials. They're the exploitation in use, a very small sized object. Bio bit is that I'm focused on helping focused on the use of biomaterials that are nanosized. So these these are very small bio-based materials, biological materials. Detecting COVID infection are a very good example of bionanotechnology in action. Uh, so, for example, there are an antibody-based test, so the key component of those are antibodies. Small molecules that can bind to other things, such as virus particles or whatever. The reason you can see the lines that form on this trip is that because the antibodies are actually stuck to a little tiny particle of gold, nano sized bits of gold, and when those anti those gold labelled antibodies come together on this trip, you can then actually see the purple band forming. So that's a very an excellent example, which now people are familiar with bio nanotechnology. And in fact, the color that you see on this when the when the line forms are the product of those very small gold particles interacting and the way they interact with light. So that would be an excellent example of buying nano technology in action, so I've previously I probably spent about 30 years. I All in all working on developing exactly those sorts of tests. Uh, I started as a student as an undergraduate on a on a work experience program develops a type of test known as analyser which made use of antibodies and enzymes. And that's also the basis of the lateral flow test that people are now familiar with, and I've also worked to develop, so I've worked over those years developing the underlying technology that leads to those lateral flow tests and other applications. Within that my focus has been sort of Environmental Quality and food safety, so I spent a lot of time working in around developing rapid tests for the for things like contaminants, additives, and detecting food fraud as well. So I did some work to develop tests.

Theme/s: Biotechnology → Bio-nanotechnology & Time-Temperature Indicators (TTIs)

- Definition of bio-nanotechnology & common example (COVID-19 antibody tests). Active bio nanomaterials react to their environment and change accordingly.
- Time-temperature Indicators can determine if food has gone bad or been mistreated in the supply chain. It is automatic and reliable and could replace use-by dates in products.
- Visual communication with the user

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Marianna Olivia Lordou (Student)

What is food fraud?

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Graham Bonwick

So food fraud is where you substitute food items with cheaper, inferior alternatives. So, a good example from recent times would be the replacement of, say, beef with horse meat. That's something that people are quite familiar with in the UK. That's relatively easy to pick up by a range of tests, so I've worked in those sorts of that sort of error detecting food fraud. Whenever this you've got expensive food items or ingredients so you can guarantee that someone is going to want to rip people off. So, a long time ago I worked on detecting different types of milk and cheese is so. For example, cow's milk is very cheap. Uh, something like Buffalo milk is way more expensive and what people were doing was just simply diluting the Buffalo milk with cow's milk, or just simply not bothering to use it at all. But it tends to be high value things that people get into, so it's typically meat, which is expensive. So, replacing expensive meats with cheaper alternatives.

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Marianna Olivia Lordou (Student)

So you're basically making rapid test for food. This reminds me of some research I've done on clamshells in food packaging. They were designed as theft-deterrents because they're very hard to open and they're very hard to hide if you're trying to steal. Are you familiar with wrap rage, and how those theft-deterrent properties interfere with the legitimate customers?

00:24:03.610 --> 00:25:49.680

Graham Bonwick

So this is a classic one, it's just it's an image you can find on the Internet there's images or things like scissors sealed into a pit package, and it's impossible to pull it apart. You must have a pair of scissors to cut your way into it, which is crazy so. But no wrap rage. Definitely we refer to that as a inclusive design is the sort of the science of designing packaging so that it's accessible to people with various issues. So, for example, many of the elderly people have problems with due to things like arthritis, so their ability to move their fingers as impaired so they can't open packaging. So your if you don't design packaging well, it can provide a barrier to certain groups of people. Or if you're a visually impaired you may not be able to read the small labeling that's on a package. Uh, I'm. I had some interaction with some students. They were masters students at the time. They had a project to try and create labels for food packaging that would tactile rather than visual. They they actually set a company up. It was called Bump Mark, but I think it changed its name such as currently, and the idea was you could feel as a as a visually impaired person, a bit like Braille. You could feel the label and as the food item approached its used by date the label actually became more and more sort of tactile, more rough. I think the idea was. So that was a really clever idea I thought was an excellent example of sort of inclusive design to try and accommodate people's abilities or disabilities.

Theme/s: Consumer Behavior & Biotechnology

- Investigate wrap rage in packaging – cause of frustration and injuries to consumers every year.
- Packaging attributes are important; wrap rage, for example, is exclusive to visually impaired and/or older consumers.
- Biotechnological tactile labels are inclusive for visually impaired people. The label changes rigidity over time, indicating that the product expired. Like Braille, people can feel the status of the food.
- Explore other biotechnologies that accommodate people's abilities or disabilities.

00:25:50.960 --> 00:25:57.540

Marianna Olivia Lordou (Student)

How would that work? How would be material property change like? How would you do that?

00:25:58.260 --> 00:26:03.870

Graham Bonwick

That's a very good and that's why I think another good example is sort of biotechnology in action. As I understand it. The material started off as a sort of a fairly solid or rigid gel. Uh, and the action of enzymes started to break it down, so as time passed it changed from a solid to a liquid and underneath this material was a rough surface. So as time went by you were able to start to feel this roughness underneath. I think that was as I understand it, that was the technology.

Theme/s: Biotechnology

- Enzymes are catalyzers and can break down matter over time. Enzyme activity could be used as time parameters for biotechnological applications, including tactile packaging

00:26:31.860 --> 00:26:37.810

Marianna Olivia Lordou (Student)

That's pretty interesting. Wow, like I'm gonna look into that. Can I find that anywhere on the Internet?

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Graham Bonwick

Yeah, I'm I can't remember their name. Uh, they they changed the companies name from Bump Mark to something else, which I can't for the life of me remember.

00:26:46.860 --> 00:27:48.040

Graham Bonwick

But so yeah, and I guess another good example of biotech and packaging, which is again on an area I got quite interested in is is the whole area of what's called active packaging and which sort of attempts to control the environment that food package has inside. So things like, uh, scavengers of ethylene gas to slow down ripening of food. Through two sort of markers or labels on the outside that show whether or not a package has been mistreated in the supply chain. So if it's supposed to being kept cold in the supply chain, if it's some point, it's been heat. It's been left out of the fridge or freezer. It's heated up. There are labels that will show that that's happened. So it's sort of a time time temperature tag up. So again, that those sorts of sort of simple by technologies can be used to to use or give information about the state of the food. It's safety, this sort of thing.

Theme/s: Biotechnology → Active Packaging - Additional research on active packaging - Examples include ethylene indicators & time temperature indicators

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Marianna Olivia Lordou (Student)

I find it fascinating how reliable biotechnology can be. It can capture any part of the process because it would simply react to stimuli from the environment through a natural process.

00:28:08.540 --> 00:28:56.570

Graham Bonwick

Yeah, so if if it's been trialed but I believe this. This is where there's often a gap between sort of science and reality. My understanding was that the temperature abuse marker has been tried by a supermarket chain and what happened was that people would buy some sort of chilled products, stick it in the boot of the car which is quite warm relatively, then go off and do things like pick up the kids from school or go shopping. The other types of shopping link. Got home, they look at the label on the pack and it's now changed color because it's it's got warm whilst it's been in the car and so now that the so the consumers then say Oh no it's gone off. It's not fit to consume throws the whole lot in the bin so. Yeah, so some work needed there still.

Theme/s: Biotechnology & Consumer Behavior

- TTI application gone wrong in a case study with Sainsburys.
- Consumer can tamper with temperature, and therefore affect the TTI status. Consumers misunderstand and throw away food.
- More research is needed for the real-life applications of TTIs

00:28:59.270 --> 00:29:31.590

Marianna Olivia Lordou (Student)

That's a very interesting point. So next question. Let's see. You've answered quite a lot so I'm gonna have to skip some. Yeah, there's one. How does bionanotechnology relate to your research and sustainable packaging? You already answered that, but could you explain kind of describe the environment of production when you are working with biotechnology? Would it be like a sterile lab?

00:29:31.050 --> 00:30:17.840

Graham Bonwick

It depends very much on on the application so. For example, if it wasn't a label-based sensor that could be on the outside of the package, so it wouldn't need to be prepared in a in a sterile environment. The one of the main considerations is whatever you have on or in the package material. It doesn't transfer into the food if it's food packaging. So that's crucial. So one of the the major constraints is that make it is making sure that there's no contamination of the contents of the packaging. So whatever you design or develop that, that has to be taken into account. But typically, no, the development of these sort of sensors and so on doesn't require sterile conditions at all.

Theme/s: Consumer Behavior → Nano-food vs. Nano-packaging

- Bio nanotechnology can be on the packaging, or directly on the food itself.
- Further research needs to be done on the safety of those nanotechnologies, especially the ones directly on food. There are less restrictions on nano-packaging, as it's not in contact with the food.
- Research consumer perception on nano-food, and whether it is controversial.

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Marianna Olivia Lordou (Student)

Would you say that the food packaging industry would take inspiration from pharmaceuticals? I assume they have that thing in common in terms of sterilization and no contamination.

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Graham Bonwick

Yeah, yeah. The food industry has to take hygiene into account because it's going to package materials that are sensitive to contamination. So yes, the requirements of food packaging or are actually quite high, not as high as pharmaceuticals though. There are slightly different concerns if you compare pharmaceutical and food packaging, but there's a lot of overlap. There's a lot of similarities as well.

00:31:08.970 --> 00:31:23.180

Marianna Olivia Lordou (Student)

So you think any sustainable innovation in the food packaging or pharmaceutical packaging industries? They could definitely impact all the others, because I feel like there will be the two hardest ones to conquer or apply circular economy principles to?

00:31:22.570 --> 00:31:30.370

Graham Bonwick

Yes, definitely. Those [food & pharmaceutical packaging] are the most challenging areas and anything you can develop them satisfies. Those areas will probably be fine to use in other areas, absolutely.

Theme/s: Pre-Existing Industry → Similarity of food and pharmaceutical packaging - It's important to acknowledge the similarity of food and pharmaceutical packaging, in terms of sterile conditions, protection of contents, preservation, etc. - Successful commercialization of biotechnological applications in the food industry, could also apply in other industries, including pharmaceuticals. - If the pharma and food industries can do it, anyone can

00:31:33.790 --> 00:31:42.420

Marianna Olivia Lordou (Student)

Does bio nanotechnology apply circular economy principles in the manufacturing process of packaging, do you think?

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Graham Bonwick

That's a very good question, UM.

00:31:45.980 --> 00:32:03.510

Marianna Olivia Lordou (Student)

Is it a sustainable practice to use bio materials? 'cause I know sometimes there's this argument that natural materials aren't always sustainable, mainly also because of costs and transportation, and even the manufacturing process itself. It might not be energy efficient.

00:32:04.490 --> 00:33:20.770

Graham Bonwick

No, that's that's very true. I think on a very high level, if you're using biomaterials then they are not generally fossil carbon based so if they degrade are decomposed by degraded or even incinerated, you're not adding to the overall carbon levels in the atmosphere, so that's good. But apart from that there if you look at the other aspects of the production and manufacture of these materials then yes, you have to take into account their carbon footprint and the energy use. I don't know to what extent that's being looked at. I can only assume that there will be a footprint associated, but I suppose also like a lot of these things, you would then have to offset that against the benefits of using this sort of technology. So if we can reduce waste, reduce the contamination environment by packaging. Uh, in encourage, it's we saw and previous recycling then if we add one and sort of weigh one against the other, it may be that the overall effect is positive. But this is why we would need to do a full life cycle analysis to understand this much better.

Theme/s: Biotechnology → Life-Cycle Analysis

- To determine the true sustainability of biomaterials and other alternatives to plastic, a full life-cycle analysis must be conducted.
- Even bio-origins of materials can be unsustainable; for example, biodegradable ‘plastic’ is not sustainable unless it is processed at a biodegradable disposal facility at its end-of-life (to speed of decomposition.)
- Even biomaterials have negative environmental impacts; an analysis will determine if the positives outweigh the negatives.

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Marianna Olivia Lordou (Student)

Do you know of any automated bio processes? Let me just give you an example because it's a bit confusing, so I was looking into nature versus machines. When you think of manufacturing you would think of a machine. Uhm, but I've done a project on mycelium, so that's mushroom technology and the whole manufacturing process is the mycelium. All it needs are proper conditions and it grows and multiplies by itself over the course of a week. The final packaging is the denatured material itself which also biodegrades and becomes a fertilizer. I was just wondering; do you know of any other biomaterials that are also the automated manufacturing process?

00:34:11.180 --> 00:34:55.730

Graham Bonwick

I think that's a good example, but probably one of the few examples that exist. I think most people who take the approach of let's, let's take and process biomaterials and use them [biomaterials] rather than ‘let's grow the packaging’. I think that's a fairly unique and excellent example, but I guess, uh, if you go back in time, people used to use things like leaves for wrapping objects, and I I know if you go to some of the Asian countries you can have things wrapped him sort of banana leaf. I guess there's a possibility of doing that, you know, but whether it can be done on a large scale, don't know that seems unlikely.

00:34:54.000 --> 00:35:13.420

Marianna Olivia Lordou (Student)

Yeah, there's this book on affordances, and it's like it's this juice box that's made of the actual fruit of the juice inside, so it's like a weird response made within Alice skin, or like Strawberry, just I just think it's very adorable.

00:35:14.150 --> 00:36:10.920

Graham Bonwick

Yeah, well, I mean again, I've seen packaging made out of, uh, various things like olive leaves as being used banana, not banana tomato vines, so the actual material leftover after picking the tomatoes that's being processed and made into I think it was tomato trays for tomato, so when the tomatoes would pack the actual board part was based on tomato vines. I think that was a composite material. There was more to it than just tomatoes, but yeah, it's a nice idea. We've actually just recently done some work on this. We've taken some food waste following food processing. We've actually taken the food waste and then incorporated it into things like board, cardboard and paper, which can then be used to package that material. So yeah, that's that's going on, certainly.

Theme/s: Biotechnology → Incorporating food waste in common biodegradable packaging

- Food waste (after food processing) is incorporated in board, cardboard and/or paper. The food waste improves the packaging's properties and reduces food waste from the environment.

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Marianna Olivia Lordou (Student)

Moving on OK and have you researched bio processes or bio technologies that dispose or manage pre-existing plastic waste?

00:36:24.540 --> 00:37:11.880

Graham Bonwick

Yes, there's. There's a lot of interest in this, absolutely. So, for example, it's been known that's I think it's the larvae of the wax moth can digest or oil based plastics, and some of my former colleagues. Uh, I know are involved in a project that is trying to, they identified the enzymes in the digestive system of the larvae gut so they know what enzymes are able to digest the plastics. Uh, I think they're trying to do now is some genetic engineering to get bacteria to produce this enzyme so that we can basically digest plastics. I think that's a fascinating here. It's a very good example of sort of biotechnology.

Theme/s: Biotechnology → Biological Breakdown Methods

- Enzymes are one of nature's catalysts/decomposers.
- Enzymes from a wax moth's gut are capable of decomposing plastic. Future applications include the artificial production of those enzymes through bacteria.

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Marianna Olivia Lordou (Student)

Just to clarify, the term is 'catalyzing' or denaturing? What's the word?

00:37:20.310 --> 00:37:27.030

Graham Bonwick

Yeah, I guess catalyze the breakdown. Yes, uh, so it's yeah. And enzymes are sort of biocatalysts basically.

00:37:28.500 --> 00:37:40.230

Marianna Olivia Lordou (Student)

Yeah, I'm really looking into nature's decomposers, that's why I have a fascination with the mushrooms but also I don't have a lot of knowledge on bacteria, enzymes or cells that could potentially do the same thing.

00:37:41.110 --> 00:38:47.780

Graham Bonwick

So there's another one which is the white fungus. I forget its Latin name. Yeah, it's uh, I can't really. It's common name either, but it's a white fungus that's found in a sort of compost heaps, and that's known to be able to break down a wide range of materials. So again, people at there's been plenty of research to try and examine. How does it do it? What are the processes that uses? Can we then if it's saying enzyme-based process, can we produce that enzyme and make use of it. Or enzymes, yeah. So yes, there's plenty of natural decomposers out there which are we're studying the definitely, and I'm also aware that people have been looking at marine plastic so people have recovered plastic that's been in the ocean for for years because it does get colonized by various microorganisms who have an ability, even if it's fairly slow to biodegrade those plastics, so that's a good place to go looking for interesting organisms and biological processes, which would be may be able to exploit for digesting plastic.

Theme/s: Biotechnology → Biological Breakdown Methods

- Mycelium (a mushroom derivative) is one of nature's catalysts/decomposers.
- Marine plastic has been colonized by various microorganisms that are slowly biodegrading its surface. Although the marine decomposition is a slow process, it has inspired scientists to explore biological breakdown processes found in nature.

00:38:49.100 --> 00:38:59.470

Marianna Olivia Lordou (Student)

So you always like must research biology and nature and literally anything you can find and get inspired by just analyse it. Try to recreate it artificially.

00:39:02.680 --> 00:39:06.140

Graham Bonwick

Yeah, bio inspired design I believe is a topic so.

00:39:07.090 --> 00:39:37.120

Marianna Olivia Lordou (Student)

Yeah, that's definitely what I'm interested in. There are some very interesting examples, but I also want to see how it would be possible to just switch from this current infrastructure of plastic and you know, use those alternatives instead and you know it also varies on the size of the company and the industry there and that.

00:39:55.270 --> 00:40:14.640

Marianna Olivia Lordou (Student)

So you said before that, new sustainable packaging should have similar qualities to plastic, or at least be as efficient as plastic. Uh, do you think in other cases the aim would be to have different qualities? Or do you?

00:40:16.700 --> 00:41:05.260

Graham Bonwick

So for example, I'll give you a quick example again with food packaging. Some food packaging has a very short shelf life. The time between production being packed and then consumed may only be a couple of days. You don't necessarily need or a oil based plastics to do that job. Some of the bio based plastics are good enough for that sort of short shelf life, so I think there's a an opportunity there to go looking at how we use packaging and then looking for situations where we can replace it [plastic] with what we might consider at the moment to be bio based packaging that that's less effective, because sometimes we just don't need the performance that those materials actually give us. So I think it's a case of looking at every sort of situation and making the right sort of decisions.

Theme/s: Pre-Existing Industry & Biotechnology - In the current industry, there are plastic packaging applications that are simply unnecessary and problematic. Those are often found in products with short-shelf lives. - Where plastic is not needed, it should be eliminated or replaced. - Biological breakdown methods can eliminate plastic, and bio-based alternatives can replace plastic used for products with short shelf lives.

Marianna Olivia Lordou (Student)

Yeah, so like you have to look at the different lifespans. And also maybe the value of the goods, the goods that are in the packaging like I'm just starting to see many themes.

00:41:17.480 --> 00:41:29.570

Graham Bonwick

Very true. I mean, there's a lot of psychology in that bit as well. I used to say to students: You know why we don't put champagne in plastic bottles? And why do we put it in a heavy glass bottle in a wooden box?

Theme/s: Consumer Behavior → Consumer Psychology

- Although plastic is cheaper, lighter and provides better protection than glass, consumers still prefer glass packaging for high-value goods. Psychologically, luxury feels heavy. For the same reason, cheaper low-value items feel flimsy and light

00:41:30.030 --> 00:41:31.020

Marianna Olivia Lordou (Student)

People want luxury.

00:41:31.690 --> 00:41:34.390

Graham Bonwick

Because luxury feels heavy.

00:41:34.970 --> 00:41:35.660

Marianna Olivia Lordou (Student)

Yeah.

00:41:35.230 --> 00:41:49.310

Graham Bonwick

If you put something in a psychologically if it feels light and flimsy, then it's probably cheap and not very good. So yeah, there's unfortunately, we've got. We've got to think about humans, and their sort of psychology as well, I think.

00:41:49.980 --> 00:42:15.770

Marianna Olivia Lordou (Student)

Yeah, that this also varies culturally and geographically as well. So how are you supposed to must satisfy everyone? OK, we talked about barriers and like liability and well. Actually, do you have any patterns or regulations in viability like restrictions for what you're doing now in terms of biotechnology?

00:42:17.220 --> 00:43:10.600

Graham Bonwick

You know the I think the main thing if we say look at food packaging, the main restrictions, the main liabilities really are around ensuring that the food materials inside the packaging are not affected by the packaging and so there are in law there are plenty of regulations actually around food packaging for us, which is in the UK, is based on European laws still, which specifies exactly what materials can or cannot be in packaging. Uh, and also specifies and describes how they should be tested. Uh, in relation to trying to prevent the transfer of materials from the packaging into the food so we don't want our packaging contaminating the food. So as long as your new biomaterials check all those boxes, you can use whatever you like.

Theme/s: Biotechnology & USA VS. UK - There are plenty of regulations around food packaging specifically for bio-nanotechnological applications in Europe and the UK. In the USA and Asia, however, those technologies have less restrictions and more successful commercialization. - The consumers are also more reluctant to nanofoods in Europe than the USA

00:43:13.040 --> 00:43:14.560

Marianna Olivia Lordou (Student)

And now some closing questions.

00:43:15.070 --> 00:43:21.840

Marianna Olivia Lordou (Student)

Uhm, do you have any quick recommendations which I know you already mentioned a lot like bump Mark, but do you have any other recommendations or titles or any names that you think will be very beneficial to my dissertation?

00:43:34.340 --> 00:44:24.430

Graham Bonwick

Yeah, sure. If you're interested in sort of technology, biotechnology and sort of packaging performance, there's an organization called a AIPI, which is the active and intelligent packaging industry association. They have very helpful, so AIPIA. Uh, there's also one called the BBIA, which is the bio based, uh? I think it's buying based industry association or something like that. So there's there's definitely a bio based materials packaging association out there, which gain has on its website lots of information and also the the I know that the people who are involved in a very sort of willing to talk as well. Yeah, so the bio based Industries Association is an excellent resource. Very very friendly people as well.

00:44:25.460 --> 00:44:32.530

Marianna Olivia Lordou (Student)
Is there anything else you would like to add in regard to what we've been talking about, like?

00:44:32.140 --> 00:44:35.120
Graham Bonwick
No, no, it's I just say it. So thank you very much for.

00:44:35.630 --> 00:44:48.690
Graham Bonwick
Uh, I'm taking the time to talk to me, it's but it's very nice to actually get asked these sorts of things because even though I might work in this area, it's surprising how many people are actually not that bothered or interested in it.

00:44:50.700 --> 00:44:52.700
Marianna Olivia Lordou (Student)
I think they should be interested.

00:44:52.120 --> 00:44:54.900
Graham Bonwick
Well, they they should be. I think it's fascinating, but so there you go.

00:44:55.710 --> 00:45:13.810
Marianna Olivia Lordou (Student)
Yeah, I honestly think this will be my future career like I'm very interested in biology and design and technical design as well, and my Honours project is also to inclusive design. But yeah, I'm gonna I think.

00:45:12.800 --> 00:45:23.270
Graham Bonwick
At exactly interesting area, I think, and I could only strongly encourage you to go down that road of fusing those different strands together, because I think that's what's needed. Definitely.

00:45:26.470 --> 00:45:31.760
Marianna Olivia Lordou (Student)
Perfect, thank you so much for taking the time to contribute to my primary research for my dissertation. I really appreciate it.

Appendix B

Interview Questions for Graham Bonwick

OPENING QUESTIONS: EDUCATION & AGRI-FOOD RESEARCH & INNOVATION

What is your name and profession?

What is the Institute of Agri-Food Research and Innovation? What is your role in the company?

You are a professor of Applied Biology – applying biology to solve specific real-world problems and creating biological products. Can you provide an example?

- What are the benefits and challenges when applying sciences into the real world? (lack of knowledge, general awareness, technology)

What is your experience in packaging, and in what industry? (This could include conventional and sustainable packaging)

- Have you researched the application of biotechnology to achieve sustainability in the packaging industry? If yes, how?
-

CONVENTIONAL / SUSTAINABLE PACKAGING

Your RSA profile mentions you are interested in sustainable packaging. Could you please elaborate on that?

How do you reimagine food packaging to be more sustainable?

Knowing and researching both conventional and sustainable packaging, what have you learned from that experience? What are your opinions on the current infrastructure of packaging?

Ideally, packaging should be both profitable and sustainable. Do you have any advice on how both can be achieved?

Does innovation in sustainable packaging require interdisciplinary collaboration? What are the various roles that are necessary for the development of sustainable packaging?

BIOPROCESSES

How do you define bio nanotechnologies, and how are they different from nanotechnologies?

Your RSA profile mentions the use of bio nanotechnology for food safety, quality, and security. How does the process work, and what are its benefits and challenges?

Does bio nanotechnology relate to your research into sustainable packaging? If yes, how?

- Could you describe the environment of production? (Sterile lab?)

Does bio nanotechnology apply circular economy principles in the manufacturing process of packaging? If yes, how?
Have you researched bioprocesses or biotechnologies that dispose or manage pre-existing waste? For example, there are mushrooms that eat plastic and are currently dumped in landfills.

MATERIALITY

Packaging manufacturing machines have been standardized in the last 60 years to form plastic – a stiff material – making it even harder for the industry adapt with alternative materials.

- What are other challenges in applying circular economy principles in the packaging industry?

Packaging in the food and pharmaceutical sector especially, must comply under criteria such as sterilization, safety, quality, and security – all of which are qualities plastic can provide. Can sustainable packaging offer the same results?

a. If sustainable packaging can offer similar qualities to plastic, what are the main obstacles that prevent sustainable packaging from feasibly making its way into the market?

Does sustainable packaging in the food industry aim to have comparable qualities to plastic, or not? Could you explain the intentions on why or why not?

SYSTEMS THINKING

Are there any enablers and barriers for innovation in the Research & Development sector for biotechnology in food packaging? This could include patents, regulations, and liability.

- Taking into consideration these barriers, how can innovation be scaled to achieve sustainability?

CLOSING QUESTIONS

Do you have any quick recommendations that would be beneficial to the development my dissertation?
Is there anything else you'd like to add regarding bioprocesses and sustainable packaging?

Appendix C

Consent Form by Graham Bonwick

Research & Creative Practice
University of Dundee

Participant Interview Consent Sheet 2020

Please tick the appropriate boxes	**Yes**
Taking Part	
I have read and understood the participant information sheet.	☑
I have been given the opportunity to ask questions about the project.	☑
I agree to take part in the project.	☑
I understand that my taking part is voluntary; I can withdraw from the study at any time and I do not have to give any reasons for why I no longer want to take part.	☑
I understand that my words may be quoted in publications, reports, web pages, and other research outputs.	☑
I agree to being photographed / filmed.	☑
I agree to my home being photographed / filmed.	☑
I agree to my workplace being photographed / filmed.	☑
I agree to my name being used.	☑
Use of the information I provide beyond this project	
I understand that the data is subject to the University of Dundee's Data Protection Policy. The student researcher will destroy all data collected on completion of the module. Staff will need to retain all work for one academic year, and after this, some work will be kept as exemplars	☑

PROF. GRAHAM BONWICK
Name of participant [printed]

G.A.Bonwick
Signature

29/10/21
Date

Project contact details for further information:

Student Researcher: Marianna Olivia Lordou

My Tutor: Shaleph O'Neill