Team Design Project

The Use of Plastic Packaging for Food Aid in Humanitarian Relief

3rd Year Michaelmas 2022 Week 1 & 2

Executive Summary

Humanitarian food aid saves lives.

Much of this aid is transported in plastic packaging, which is rarely disposed of appropriately. This can severely affect the local environment and health of the very communities which the aid is intended to help.

Current waste management involves open burning of plastic to reduce the volume of waste, but this requires the waste to be collected.

In this report we have quantified the extent of the environmental and health concerns that arise as a result of mismanagement of plastic waste generated by humanitarian food aid. Initiatives have been proposed to sustainably deal with this waste, however cost and logistical issues remain the key barriers to their implementation, especially in the dynamic, often war-torn settings where food aid is most needed.

Mismanagement of plastic waste in the poorest areas, where humanitarian aid is most needed, raises severe health concerns. Toxic chemicals are released during burning, and drainage systems are blocked by openly dumped waste, promoting waterlogging which creates breeding grounds for mosquitoes, increasing the risk of vector-borne diseases.

This report finds that in the absence of waste management when the last-resort options available are open burning and open dumping, open burning is only preferable in two cases: for biohazardous waste, to sterilise it, and when open dumping poses a risk to drainage systems, to prevent waterlogging.

In the long-term however, alternative materials are needed to cut out the need for a waste management infrastructure entirely. We have identified chitosan and poly(lactic acid) (PLA) as candidates for biodegradable packaging materials, however further research is needed to bring these solutions to market.

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1 Introduction

1.1 Background

Plastic is a ubiquitous material that has dramatically changed the world since the first synthesis of Bakelite in 1907 [1]. Its functional properties and low manufacturing cost make it versatile and attractive for many applications, including single-use plastic. Annually, 400 million tons of plastic waste is produced (only 9% recycled) and it is projected to reach 1,100 million tons by 2050 [2]. Plastic packing makes up 40% of plastic use and is a USD 495.67 bn market [3]. PET, HDPE, LDPE, PVC, PP, and PS are the typical plastics used in packaging, depending on the form and functional requirements.

1.2 Our problem

Fig.1.1 Plumpy'Nut - Metallised Plastic Sachet example [4]

For packaging humanitarian food aid items, plastic sachets are widely used due to their flexibility and ease of packing. However, this presents environmental and sustainability challenges. The packaging material must meet its primary aim: safe storage of food, sometimes for long periods of time, ready to be deployed in response to a humanitarian need. However, without proper management there are long-term consequences.

Plastic waste contaminates the local environment, causing long-term damage to already vulnerable communities. Many incinerate these unrecyclable metallised plastic sachets, but this releases harmful fumes and greenhouse gases. While there have been initiatives to upcycle packaging into useful items, providing employment opportunities, there is a low economic drive for any complete recycling schemes [A]. Solutions for plastic recycling and reuse involve infrastructure, logistics and understanding of the culture of the displaced communities. This is feasible for some established refugee camps such as the 'Cooper's Camp' in West Bengal, India for 70 years [5], yet the lifetime of a refugee camp is generally hard to predict. Finding a solution that works for all camps and addresses the short term and long term needs is a challenging goal.

1.3 Our report

In this report, we first define the scope of the issue, quantifying the problem in terms of the amount of aid sent, the waste it produces, and criteria the packaging must meet. We then explore the sustainability of current and proposed initiatives for mitigating impacts of plastic waste, including incineration and recycling programmes. In contrast, we subsequently take a blue sky approach, reviewing possible alternative materials for plastic packaging. These have the potential to provide a straightforward solution without complex logistical requirements for recipient countries. Each solution we discuss is assessed for both environmental and economic sustainability. Finally, our findings are summarised and we suggest possibilities for improving the sustainability of humanitarian aid in the long term. Our primary focus is identifying promising areas for the future, whilst also suggesting shorter term initiatives that could be implemented sooner to reduce the damage. This report is not a prescriptive proposal for a single solution that eliminates all issues with plastic waste from humanitarian food aid, but is rather a pragmatic assessment of what can realistically be done to improve a situation fraught with uncertainty and instability.

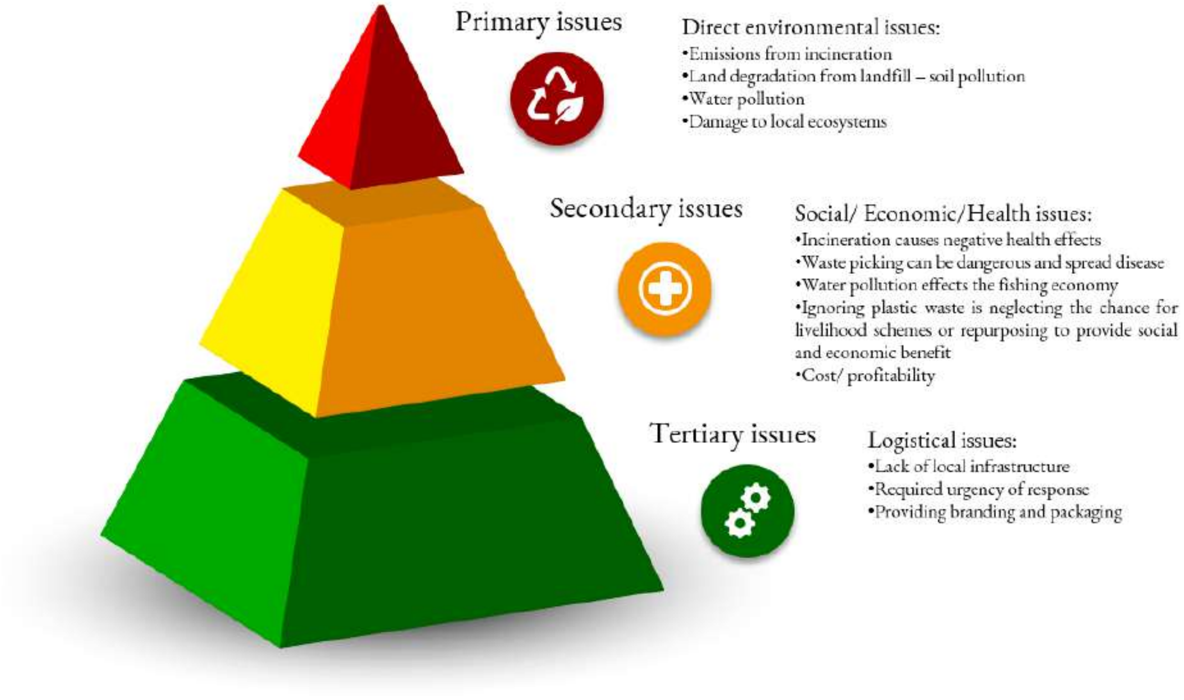
2 Scope

2.1 Defining the Problem

The multi-faceted nature of the plastic waste issue is summarised by the tiers in Fig.2.1. Tackling all aspects requires a comprehensive range of research and schemes beyond the scope of this report.

Accordingly, we confine the problem to plastic food packaging primarily composed of polypropylene; specifically, we are focusing on plastic bags, and aluminium laminated polypropylene peanut paste sachets. This is discussed in the following section.

The key problems raised here are, therefore, the effects of persistent plastic waste in the environment. **Our aim is to mitigate these effects.**



ZY - Fig.2.1 Issues Hierarchy

The primary focus is to reduce the environmental impacts of plastic waste from humanitarian food aid, mainly the volume of plastic that ends up in local communities and waterways. We therefore consider schemes for directly removing the waste, for example by incineration, as well as ways to prevent the waste becoming a problem in the first place, for example by using a biodegradable material alternative.

We must also consider the effects on people, particularly health concerns. This involves reducing toxic emissions into the air and impacts on local food networks.

Our solutions must also be evaluated in terms of practicality; if a proposal is not viable logistically, it is not worth pursuing further. Although we may consider solutions where further scientific work is required, we are hesitant to recommend initiatives that require significant new infrastructure in areas where the aid is being received.

The final consideration is the scope of the problem itself. Our brief is to reduce the effects of plastic waste, and all suggestions here are prioritised in this context. The aim is to propose a range of solutions that may be applicable depending on the circumstances that aid is required. More unstable situations require solutions that are faster to implement, without necessarily being perfect in their execution. There will be no single silver bullet, but our solutions must strive to meet the criteria defined here, as well as the detailed specification outlined subsequently.

2.2 Quantifying the Plastic Problem

The problem of plastic pollution in humanitarian aid was first highlighted by Charles Parrack, technology subject lead at Oxford Brookes University. We then went on to research the context of food aid, current approaches, and an outline for a materials solution which we cover in this section.

2.21 Food aid - How much? What is it? Where is it sent?

Data from WFP, UNICEF, ICRC and UNHCR showed 6.7 million tonnes of food and non-food items are used for humanitarian aid, with 6.65 million tonnes of food purchased [B]. This results in 32,000 tonnes of primary packaging and 35,000 tonnes of secondary packaging. Rice, sorghum/millet, wheat flour, wheat and vegetable oil are the main items distributed by mass. The main recipient countries of food and non-food relief items are Yemen, Ethiopia, Syrian Arab Republic receiving 16,000, 8,000 and 9,250 tonnes of packaging from the aid [B].

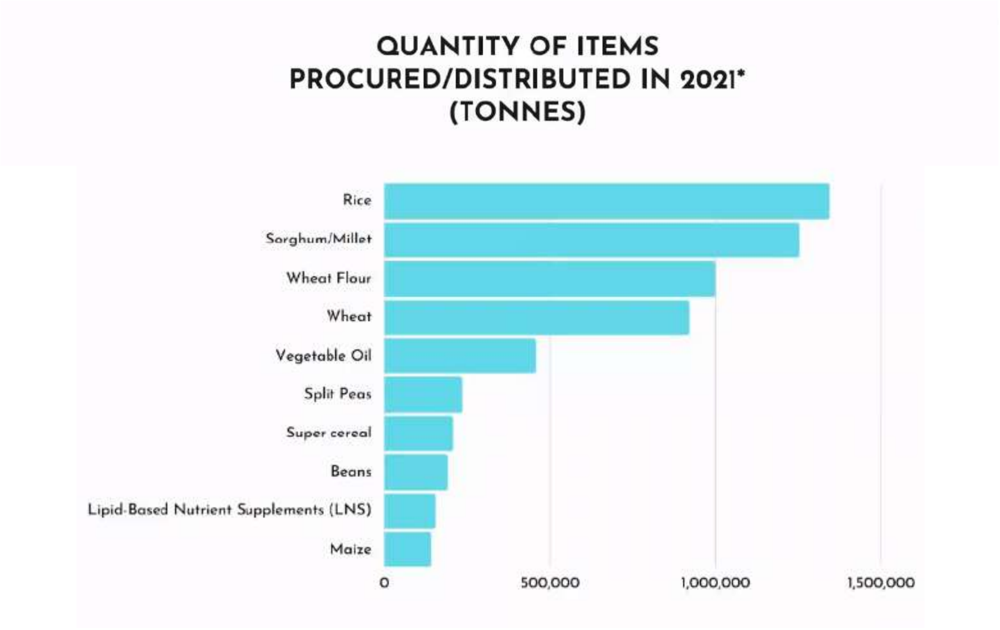


Fig.2.2 Quantity of Items procured/distributed in 2021 (tonnes) [B]

Aid is primarily donated by the US, EU, Canada and Japan. Refugee camps typically exhibit poor infrastructure and low education levels. Consequently, there is a severe lack of effective recycling schemes. Instead, approximately 8.1 million tonnes of waste is generated annually. A significant amount of this is plastic. It is estimated that over 1700 tonnes of (mostly recyclable) plastic waste is produced per year, but underfunded waste collection services and lack of recycling infrastructure mean the camps are flooded with waste plastic; resulting in sanitary and transportation problems[6].

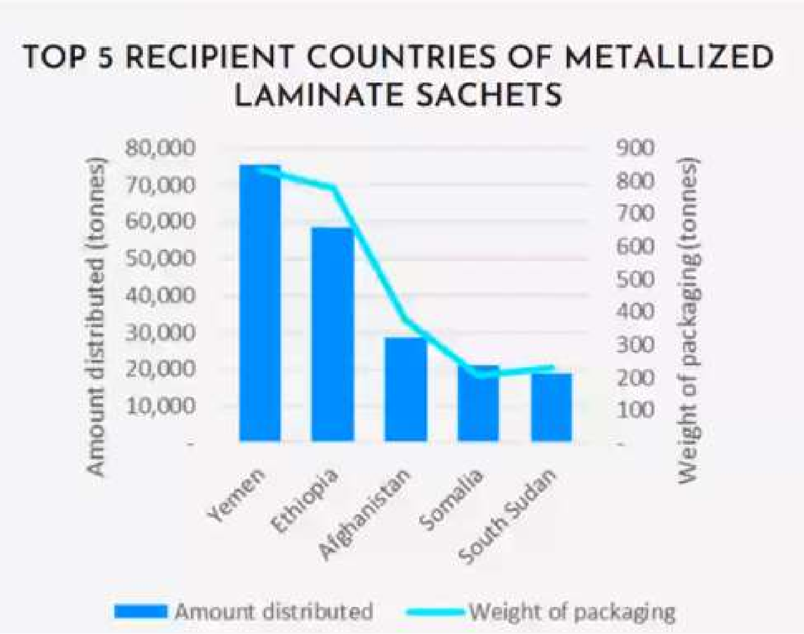


Fig.2.3 Recipient countries of metallised laminate sachets [B]

2.22 Recycling schemes

From the IOM study of five displacement camps in Kenya and Uganda on waste from solar panels, it is noted that over 50% keep the waste at home and or throw it away in nature. This demonstrates that there is motivation to repair and recycle the waste. However, this is limited by a lack of infrastructure, repair shops and recycling centres in regions receiving humanitarian aid [7].

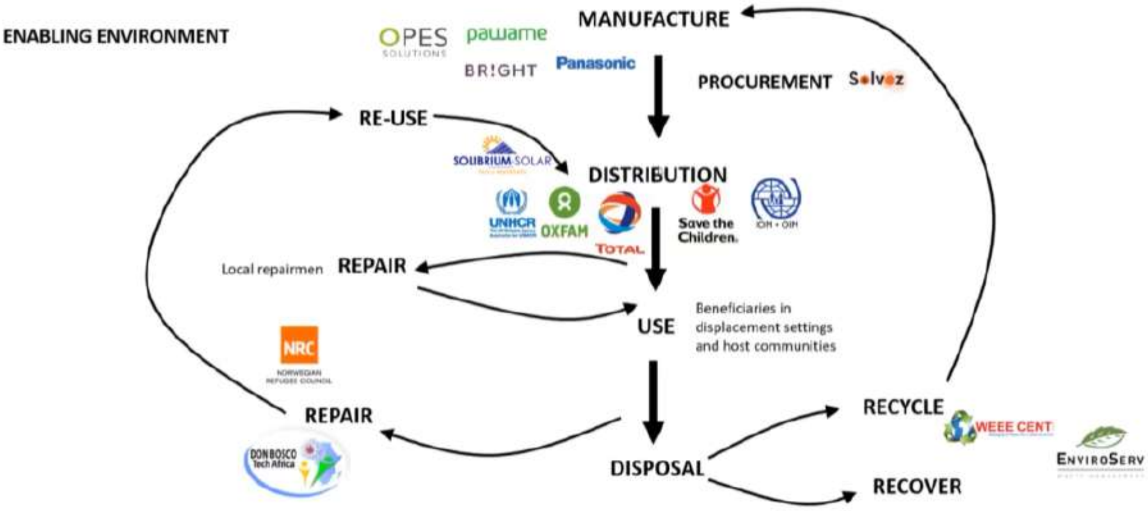


Fig.2.4 IOM Ecosystem Analysis - stakeholders and local context [8]

Considering the ecosystem of plastic packaging in humanitarian aid, there are many stakeholders and components. Fig.2.4 shows that each step involves separate logistics and transport difficulties. They are all intertwined at a system level in waste management, policies and regulatory requirements as well as at the individual level in the perception of the end of life of plastics.

At the manufacturing stage, companies such as Opes Solutions are tackling the problem by making solar panels from recycled materials, while technical skill distribution organisations such as Don Bosco Tech Africa teach processes for the repair and reuse of products. Take-back systems for recyclable material have been suggested, similar to the WEE requirements in the EU region for electronic waste, that make use of current infrastructure [E]. Establishing such a system would be resource and time intensive, requiring current suppliers or freight forwarders to work with humanitarian agencies, collecting recyclable materials on delivery runs, minimising the carbon footprint and avoiding one-way transport costs. Since building systems and coordinating initiatives takes time and planning, it does not fit the unpredictability of natural disasters. As such, passive material solutions are ideal candidates to cope with ecosystem and behavioural problems.

2.23 Logistics

Searching for a materials solution first necessitates the consideration of key logistics. The pipeline of humanitarian aid involves the storage of food stockpiles for up to 2 years. After aid is requested, transportation is arranged [G]. 5,600 trucks, 50 ocean shipments, 92 aircraft and a network of 650 warehouses from WFP deliver food and other assistance each day [9]. Flights from the US, or Japan, to Africa take 15-24hrs, and normal shipping takes about 8 days from the US to Africa. Land distribution often results in significant delay in disaster-stricken regions.

Consideration must also be given to plastic-related restrictions i.e Kenya, Rwanda, and Tanzania limit the use, manufacture, and import of plastic films of a certain thickness, directly affecting humanitarian assistance operations. Imports or deliveries failing to meet stated requirements are rejected, and in some cases, organisations can no longer import products containing plastics. A UNHCR emergency stockpile in Tanzania maintained for rapid response in the region was partly closed due to the new plastic-related import restrictions. This is a point of further research beyond our report.

2.24 Metallised sachet packaging

Our research investigates the use of polypropylene (PP) in food packaging in humanitarian aid. This includes metallised laminate sachets and woven bags, at an annual consumption of 4,100 and 15,000 tonnes respectively.

Metallised laminate sachets make up 13% of the total primary packaging. Currently, polypropylene sachets are laminated with aluminium for its barrier properties. An option is to replace the polypropylene with a biodegradable plastic and laminate it to the aluminium. This is detailed in Section 5.

The performance requirements are determined by the conditions during storage and transport as mentioned in (logistics section), and the food that is packaged. This must be considered to ensure the longevity of goods, and is considered in Section 3.

Our report focuses on dry food, particularly super cereal packaging, which makes up 48% of metallised laminate sachets. A solution to the dry food problem that satisfies the performance requirements, FDA and USDA certifications, [10], can be adapted to other forms of primary packaging and food types such as rice and wheat which make up a significantly larger proportion of humanitarian aid provisions, as mentioned before and seen in Fig. 2.2.

This brief consideration of the use and logistics of packaging allows us to look at defining a product description and considering the solution specification. The following section details this further.

3 Materials Criteria and Specifications

3.1 Product Description

Simulating the real conditions in the food aid programs that the majority of food aids (usually contain dry food such as cereal, rice, pasta, biscuit, and UHT milk) are shipped from the U.S. to refugee camps in Africa and then distributed, and the recipients store the food bags in their temporary tents for long-run consumption, we recognised core demands on the quality of the alternative materials:

- Capable of long-time storage (longer than 2 years).
- Great UV barrier.
- Low Water Vapour Transmission Rate (e.g. lower than 1.5 $g/m^2/day$).
- Low Oxygen Permeability (e.g. under 1 $cm^3\ d^{-1}\ m^{-2}\ bar^{-1}$).
- Biodegradable to be recycled properly in recipient countries.
- Nontoxic and chemically safe enough to contact with food.
- Good strength performance.
- Great high temperature resistance.

More specific experimental details and methods about the criteria will be stated in the paragraphs below, with the reasons and assumptions we made for the setting of spec values.

We propose 20 pieces of each candidate material to undergo each spec's (e.g., 90℃ for 24 hours) test if not specified as it is an adequate amount to show the group performance while keeping the cost relatively low.

3.2 Product Specification

3.21 Chemical Resistance

- Spec: Pass the *FDA Approval* and *ISO 9001 Manufacturing Certificate*.
- Test Method: The components of candidate materials have to meet the baselines stated in *FDA Approval* and *ISO 9001 Certificate* for food-contacting safety[11].

- As a global food packaging safety standard, the *FDA Approval* directly indicates the applicable materials including:

  1. Plastics (Polyolefins, polyesters, polystyrene, polyamides and many more)
  2. Paper and cardboard
  3. Polymeric coatings
  4. Additives
  5. Adhesives

  in the *21 CFR parts 170-199* regulations. The FDA document gives the standard list of reactants (the food or chemicals that are likely to contact with food packages) that will contact the test samples with the specific contacting durations, and materials do not show defects or reactions after the test could be proved as "food-safe" by the certified inspector[12].

ISO 9001 is another certification with similar examine procedures[13].

Examples of currently used food-safe packaging polymers are listed below:

1. Polyethylene terephthalate (PET)
2. High-density polyethylene (HDPE)
3. Polyvinyl chloride (PVC)
4. Low-density polyethylene (LDPE)
5. Polypropylene (PP)
6. Polystyrene (PS)

And considering the chemical formulae of the common oil and acidic food components, here are several examples of the reactants that packaging plastic must not react with:

- Triglycerides in vegetable oil

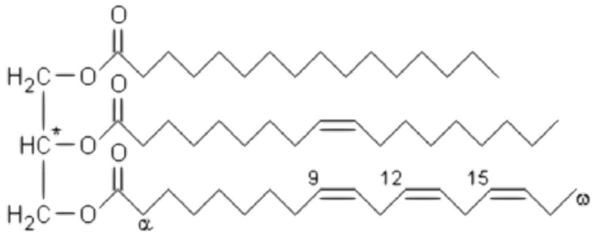


Fig.3.1

- Elaidic Acid in meat fat

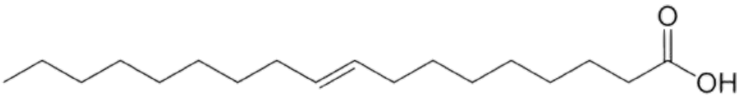


Fig.3.2

- Citric Acid in lemon acid

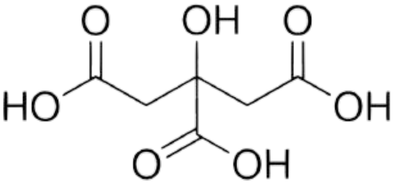


Fig.3.3

3.22 High Temperature Resistance

- Spec: No chemical released or physical performance degradation after the Heat Soak and Thermal Cycling Test.
- Test Method: Each plastic sample will be left in a heat chamber under 90℃ for 24 hours Heat Soak Test.

  In the Thermal Cycling Test, each sample will undergo a 3-days alternation of 20℃ and 90℃, with 12 hours for each section (i.e., 12 hours 20℃, 12 hours 90℃, then 12 hours 20℃...).

- The high and low temperature limits are set from the weather data that the ground temperature of Africa can be higher than 80℃ in summer and the temperature in shipment is about 26.2 ± 2.3℃, while Kenya's night temperature is about 25-30℃.

  The 24 hours duration spec for Heat Soak comes from analysing the car transportation time from Kenya's only port Mombasa to the four world's largest refugee camps Kakuma, Hagadera, Dagahaley, and Ifo[14].

  Then, by including the time for loading and food distribution at camps, we assume that the plastic packages will undergo 3-days thermal cycling in maximum due to day-and-night cycles.

3.23 UV Light Resistance

- Spec: No photodegradation (such as chalking, loss of strength, and increased brittleness) or shorten in lifespan after UV Light Test.
- Test Method: Test samples will be left in a UV chamber with a beam of 295 nm wavelength for 3 days.

- The UV lights causing concerns lie in the wavelength range of 295-325 nm[15] with the 295 nm beam giving the strongest burning energy.

  The 3-days UV exposure duration is set by assuming that the plastic packages are exposed to the strong natural UV light for up to 3 days for car transportation and camp distribution.

3.24 Humidity Resistance

- Spec: No physical damage or gas or liquid leakage after the Humidity Test.
- Test Method: Samples will be left in the humidity chamber with Relative Humidity (RH) =90% for 28 days.

- The extreme condition of ferry shipment has an environment with RH=90%[16], and the business goods shipment from the U.S., the current world's largest food aid donor, to Kenya takes 5-25 business days. Besides, the shipments take around 3-4 extra days to discharge the goods, which means that the food bags will be immersed in highly moisturised environment for about 28 days.

3.25 Sealing

- Spec: Dye Developer Result should be negative after the Dye Penetration Test.
  The Water Absorption and Water Vapour Transmission of the material should not be much higher than those of the existing food packaging plastics as listed below:

Material	Water Absorption w/w/day	Water Vapour Transmission/(g/m^2/day)
Polypropylene (PP)	0.03%	1.4
Polycarbonate (PC)	0.02-0.3%	15
Polyvinyl Chloride (PVC)	0.08%	1.1

Table.3.1 Permeability constants of current packaging polymers

- Test Method: Dye Penetration Inspection (DPI) looks for the cracks, leaks, or pores on the post-manufacturing materials in the scale of up to micron[17].

  After the sample surface is cleaned and dried, the penetrant which is normally a combination of carrier (water/oil/alcohol) and dye will be applied evenly onto one side of the samples' surface and left for 30 minutes to "dwell". Then, extra penetrants on the surface will be gently wiped (but make sure not to wipe out the penetrant that has penetrated the sample)[18].

  Spray the developer on the other side of the plastic sample and inspect if any penetrants pass - negative result indicates that penetrants do not pass through the package[19]. Also note that the result becomes meaningless if the penetrant melts the plastic and creates the pore or defect.

  Repeat the procedure under 90℃ to examine if the result is still negative.

- For hygiene reasons, the food packages should not have any water or gas leakage. Plus, due to the transportation environment, poor sanitation in refugee camps, and the prevailing virus illness in Africa, it is also crucial to expect the plastic packages to block the bacteria and virus, even under high temperature. So, the developer result is expected to be completely negative in DPI and the test should be repeated under the 90℃ high temperature.

  Polymer's sealing capabilities can also be compared in the Water Absorption and Transmission perspectives. Water Absorption value indicates ratio of mass of absorbed water to the plastic sample's original weight after soaking in water for 24 hours while Water Vapour Transmission shows the amount of water passing the plastic sample per day. Compared with the Water Absorption and Vapour Transmission performance of current food package materials, the alternative materials should not perform much worse than the existing materials.

3.26 Cutting Resistance

- Spec: Cutting Resistance or Strength is expected to be as high as possible.
  The strength performance is expected to be better or similar to the current major food package plastics as listed below:

Material	σy/MPa	σ/MPa	Elongation at Break	Elongation at Yield	Elmendorf Tear Strength MD/g	Elmendorf Tear Strength TD/g
Polypropylene (PP)	12.0-43.0	15.2-45.0	3.0-1900.0%	7.0-14.0%	20.4-33.6	40.8-204.0
Polycarbonate (PC)	39.0-70.0	28.0-75.0	10.0-138.0%	3.0-50.0%	N/A	N/A
Polyvinyl Chloride (PVC)	3.5-73.1	14.3-53.7	2.0-330.0%	3.1-6.0%	N/A	N/A

Table.3.2 Strength performances of current packaging polymers

- Test Method: Elmendorf Method of Tearing Resistance Test could be employed to test samples' tearing resistance[20].
  In the test, the tested sample is clamped on the machine and an initial cut will be made in machine direction (MD) or transverse direction (TD). A pendulum then falls to tear the sample along the pre-cut direction with a force, and the force can be read from the machine.
  Besides that, the material samples would also undergo normal tensile tests to examine for the yield and tensile strength values for comparison.

- It is possible for the plastic sachets to experience unexpected drops, drags, or cuts during transportations and storage. Therefore, polymers with better strength performance will always be preferred.

3.27 Drop Strength

- Spec: No structural damage which will affect the preservation of food after the Drop Tests.
- Test Method: The container of the food will be dropped from height 1.2m in the angle of side, bottom, or edge between side and bottom hitting the ground first each.
  The procedure is repeated in height 2.2m, 3.2m, and 4.2m.

- It is important for the food bottle-like packages to stand the drop or strike during transportation. Since the drop happens most frequently during the car transportation of food aid, the height of trucks and the containers are used to decide the height in the drop test.

Bottom of container to ground/m	Height of container/m	Possible drop height
1.2-1.5	2.0-2.7	1.2-4.2

Table.3.3 Height of general truck and container

Thus, the possible dropping height for the bottle lies in the range of 1.2-4.2m, and the tests can be carried out using 1m height intervals.

3.28 Compression Strength

- Spec: The package does not show physical shape change that will affect the quality of food preserved inside it after the compression is applied.
- Test Method: The plastic food container samples will undergo a 50kN pressing load in the Zwick Z3050 machine[21].

- Due to the stacking of the food during transportation, the food container must be able to withstand a high compression and preserve the quality of food inside if it is a bottle or tin.

3.29 Capacity

- Spec: Maximised capacity under the same volume is preferred.
- Test Method: Burst Strength Test is employed to measure the package's maximum capacity by increasing its internal pressure until the seal bursts[22].

3.30 Environmental Effect

- Spec: Biodegradable in the recipient countries and minimal plastic usage in packages.
- Assess Method: The extent of materials' recyclability depends on its component and according to Danish Refugee Council (DRC), a leading international humanitarian nonprofit organisation, the package recycling also includes reusing it for other purposes or creating other job positions via the dumped package in the local region. In addition, the package should be designed according to the food's size and shape to avoid the overuse of plastics[23].

3.31 Cost

- Spec: Cost of manufacturing, transporting, and finally recycling or dealing with the packages must be minimised.
- Assess Method: The total cost spent on a type of packaging materials during a food aid program depends on various factors, including the manufacturing methods, ways to deal with the materials at recipient countries, and even ways of transporting the certain type of food aid, etc. The food aid associations would try to save the overall cost on packages by considering all the affecting elements. Since better performance in criteria usually links to higher cost, i.e. polymer with better strength needs more cost to manufacture, it is essential to balance between the cost and plastic quality.

The criteria in the section serve as indicators to rate the alternative material solutions in conclusion of Section 5. The materials' properties are listed quantitatively in a table at the end of Section 5, with the good performance labelled in green, moderate in yellow, and poor in red. Therefore, the pros and cons of candidate materials can be visually shown to suggest a material selection intention.

4 Prior Art - Incineration and Upcycling

4.1 Introduction to Current and Proposed Practical Solutions

In the following section, we investigate how and why developing countries currently use landfill, open burning & recycling to deal with their plastic waste. We outline a calculation for quantifying the harmful effects of these schemes, helping define the extent of the issue and understanding the potential for improvements. We specifically look at polypropylene bags and metalized polypropylene sachets, and how they are dealt with.

4.2 Methods of Calculation

To quantify the effect metalized polypropylene sachets have on the environment, an estimation for the CO2 equivalent of how many sachets are sent out for aid a year was calculated.

$$CO_2\, Equivalent \ = \ Mass \times GWP \tag{1}$$

Where the mass is in metric tonnes and GWP is the Global warming potential of the gas.

In our calculation we estimated how many metallized polypropylene (PP) sachets of peanut paste are sent out a year to provide critical malnutrition aid. According to RUTF, global budgets cover malnutrition aid for 2.7 million children [24]. We assume the majority of this aid is provided to children under the age of 5, as UNICEF states that treatment of malnutrition in the first 1000 days of life is the most critical [25]. RUTF states 3 packets a day for an average of 7 weeks as the typical amount a child needs to recover from malnutrition, amounting to approximately 400 million metalized sachets a year.

4.3 Landfill

Landfill is the most common method of waste disposal in many countries (Fig.4.1). It is likely chosen by developing nations because it is the lowest cost disposal option and one of the only options available in an area with limited waste management infrastructure.

Often in developing countries, there is a lack of awareness and education on the issues associated with simply discarding waste and allowing it to amalgamate as landfill. Furthermore, people receiving emergency food aid are unlikely to prioritise the disposal of plastic food packaging waste. Consequently the responsibility falls upon those providing humanitarian aid, leading to logistical difficulties. According to the waste hierarchy (Fig. 4.2), landfill comes under the disposal category - one of the worst options - yet it is still the most used. This shows developing countries simply have no alternative to the disposal of plastic waste. However, this presents many problems to both public health and the environment.

4.31 Environment

Landfill often leads to an irrecoverable loss of resources and land, as often landfill sites can not be used to build upon due to potential engineering or health risk reasons. As well as being the source of unpleasant sights and odours, landfills can release hazardous substances through the escape of leachate created by combined biological, chemical, and physical processes [26]. Small particles and fibres, including microplastics, can be transported to the surrounding soil, by leachate and air, which has been shown to decrease the number of species that live below the surface which maintain the fertility of the land [27]. When plastic particles break down, they gain new physical and chemical properties, increasing the risk that they will have a toxic effect on organisms and the surrounding environment.

4.32 Health

There is a general lack of quality data on the health impacts of various waste management options, much less plastic waste, based on epidemiologic studies. However, small risks of birth defects in families living near landfill sites have been identified [28]. Chemical effects are especially problematic at the decomposition stage as additives such as phthalates and Bisphenol A (BPA) leach out of plastic particles. These additives are known for their hormonal effects and can disrupt the hormonal system. In addition, nano-sized particles have been shown to cause inflammation and even cross tissue barriers allowing interactions with single cells which trigger changes in gene expression and biochemical reactions [29].

Fig. 4.1 - Plastic post consumer waste rates of recycling, energy recovery and landfill per country in 2018 [30]

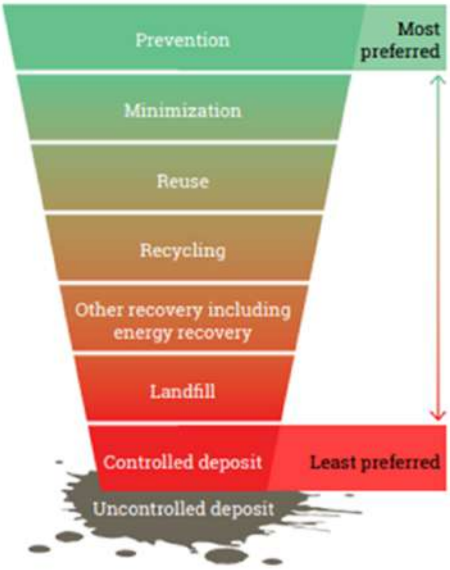


Fig. 4.2 - The 'waste management hierarchy' ranking waste management options according to what is best for the environment according to the Waste Framework Directive [31]

4.4 Open burning / Incineration

As landfill overflows, countries eventually resort to burning waste to reduce the space it takes up. As suggested in Fig.4.2, recovery of energy by burning plastic waste in a plant compliant with the Waste Incineration Directive is thought to have a less significant environmental impact [32]. Therefore, all incineration of waste should be performed with an appropriate filter system to trap and prevent the release of toxic substances; ensuring incinerators operate in a way not to pollute the atmosphere, soil, and groundwater. This is where the issue arises in developing countries without the means to incinerate the plastic waste properly and no kind of efficient 'energy recovery' can be done to use the waste as fuel. However, since countries still need to reduce the amount of waste, they often open burn their waste material as this can reduce the mass by 75 wt.% [33]. This is likely because, similar to landfill, it is the cheapest available option to deal with the waste without a more appropriate waste management system.

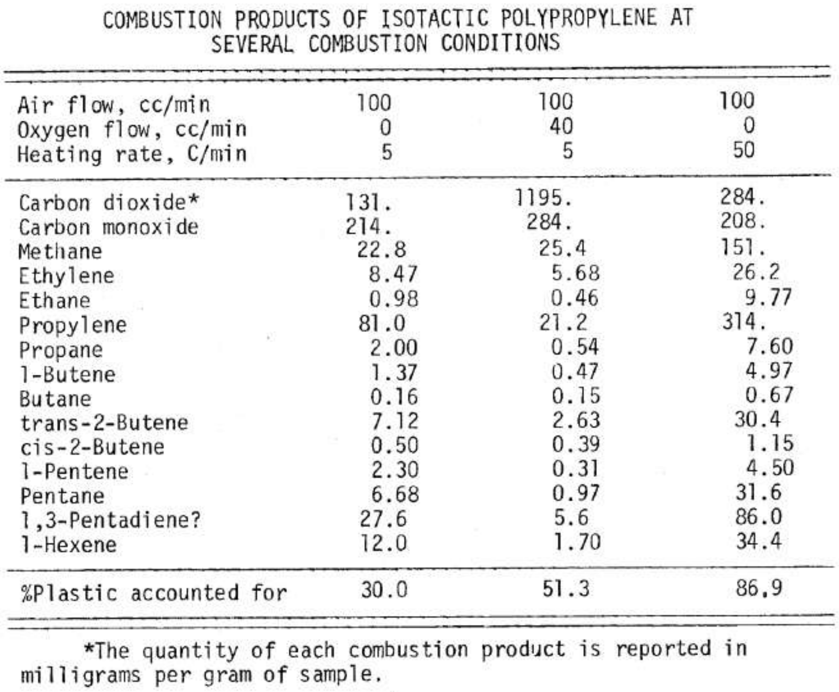
4.41 Environment

The environmental impacts of incinerating plastic waste, as with most solid wastes or fuels, includes airborne particulates (including microplastics) and greenhouse gas emissions.
Considering our estimate of 400 million metalized PP food aid sachets sent out a year, and assuming a single sachet contains 1 gram of pure polypropylene (rather than being bonded to an aluminium layer), an upper limit on how much the CO2 equivalent is from the open burning of these sachets can be formed.

Table 4.1 shows results of a study performed by Michigan University for the environmental protection agency. The column on the right best simulates open burning as it is a large uncontrolled change in temperature with often incomplete combustion occurring due to an insufficient oxygen flow. We can see the key greenhouse gases produced are CO2 and methane during the combustion of polypropylene, these values being higher when incomplete combustion is occurring.

Using the calculation demonstrated in the methods section above, we calculated a CO2 equivalent of 1623 tonnes a year from burned polypropylene sachets. To put this into context, this would be the equivalent of the CO2 emissions from the average usage of 1000 cars a year.

Furthermore, the open burning of waste causes air pollution and affects air quality. The results of a study aimed at investigating the environmental effect of the burning of open refuse dumps showed that the oxygen levels for all the locations under the different conditions tested ranged between 14.2% and 17.5%. This showed that whether the dumpsites were burning or not the oxygen levels within the vicinity were below the comfortable level of 19.5%. CO levels ranged between 2 ppm – 9ppm. CO2 values, which ranged between 361 ppm to 700 ppm, are all higher than standard acceptable levels of 350 ppm. The implication is that burning refuse in the open increases the quantity of CO and CO2 in the atmosphere which will likely cause adverse health implications to the residents living close to such areas [34]. Ash produced during burning pollutes soil, groundwater, lakes, rivers and streams which can then cause problems with agriculture and fertility of land and become harmful to natural wildlife physically or by contaminating ecosystems.



COMBUSTION PRODUCTS OF ISOTACTIC POLYPROPYLENE AT SEVERAL COMBUSTION CONDITIONS

Air flow, cc/min	100	100	100
Oxygen flow, cc/min	0	40	0
Heating rate, C/min	5	5	50
Carbon dioxide*	131.	1195.	284.
Carbon monoxide	214.	284.	208.
Methane	22.8	25.4	151.
Ethylene	8.47	5.68	26.2
Ethane	0.98	0.46	9.77
Propylene	81.0	21.2	314.
Propane	2.00	0.54	7.60
1-Butene	1.37	0.47	4.97
Butane	0.16	0.15	0.67
trans-2-Butene	7.12	2.63	30.4
cis-2-Butene	0.50	0.39	1.15
1-Pentene	2.30	0.31	4.50
Pentane	6.68	0.97	31.6
1,3-Pentadiene?	27.6	5.6	86.0
1-Hexene	12.0	1.70	34.4
%Plastic accounted for	30.0	51.3	86.9

*The quantity of each combustion product is reported in milligrams per gram of sample.

Table. 4.1 Data on Combustion products of polypropylene [35]

4.42 Health

Open burning does reduce the risk of infection from decaying waste due to the heat reducing bioactivity, but this is at the cost of serious potential risk to public health from substance emissions. There are an estimated 270 000 premature deaths per year worldwide from the open burning of waste [36, 37]. Importantly, no study as yet has attempted to collate and summarise evidence that focuses on the human health impacts of the open burning of plastic waste as a distinct material group. But these values quantify the negative health impact this method of waste management can have.

When plastic waste is combusted, a range of substance emissions can occur. Usually these are from additives added either intentionally or unintentionally to the material which then may escape during combustion and create atmospheric and terrestrial pollution. The burning of plastics often causes the realease of dioxins which can settle on crops and waterways, entering the food chain. Dioxins have been shown to act as carcinogens, cause neurological damage and disrupt reproductive thyroid and respiratory systems [38].

4.43 Mortality

Tearfund – an international relief and development charity – estimated the global deaths due to mismanagement of waste to be between 400,000 and 1,100,000 annually, with the lower and upper bounds of deaths caused by open burning being 270,000 and 920,000 [39], placing the lower and lower upper bounds of other deaths at 130,000 and 180,000. Hence open burning accounts for between 60% and 88% of deaths caused by mismanaged waste.

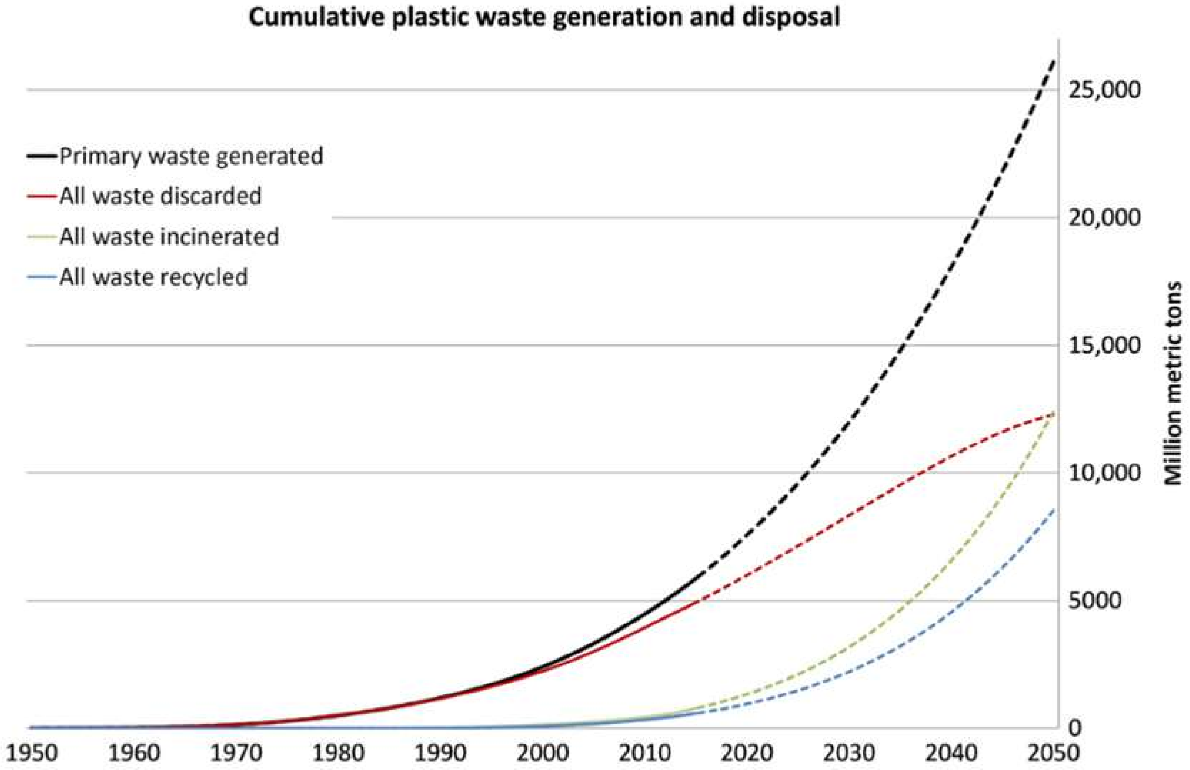


Fig.4.3 – The fate of plastic waste from 1950-2015. Incineration describes all burning, discarding describes both landfill and waste in nature [40]

Fig.4.3 demonstrates that despite being a small portion of total waste, open burning accounts for the majority of deaths. If open burning increases at the projected rate, this number could increase catastrophically.

4.5 Waste in the Environment

Other places plastics may end up include the ocean, or as general litter, which can be very damaging to ecosystems and difficult to recover. These can produce environmental microplastics which enter food chains. This section discusses what happens when there is no waste management, and emphasises how avoiding these is a primary aim of this project.

80% of ocean plastics come from land-based sources, of which three quarters are due to a lack of efficient collection schemes and waste management systems [41].

This isn't just an issue in coastal areas, w.ind and rainwater can carry plastics large distances to streams, rivers and drains which lead to the ocean. Plastic waste pollution in aquatic ecosystems is projected to nearly triple by 2040 without meaningful intervention, according to a United Nations Environment Programme report into marine litter and plastic pollution [42].

The same report listed the following key findings, which will only get worse with increasing marine litter:

- "Plastics are the largest, most harmful and most persistent fraction of marine litter"[42]. When they break down in marine environments, they transfer microplastics, toxic chemicals and other pollutants including heavy metals into water and eventually food chains. This is not only damaging for ecosystems, but also for global carbon cycling. 50-80% of Earth's oxygen production comes from the ocean, primarily from plankton but also from mangroves, seagrasses and corals, all of which are affected by plastic pollution.
- Human health is at risk; ingestion of seafood contaminated with chemicals associated with plastic pollution can have endocrine disrupting properties. While the extent of the health problems is unclear, some of these chemicals are associated with serious health impacts, especially in women. Coastal and indigenous communities who rely on marine species as their main source of food are most at risk.
- There are hidden costs to the global economy. Marine litter presents a serious threat to the livelihood of coastal communities as well as to shipping port operations. The cost to tourism, fishing and aquaculture industries, together with other costs including clean-ups, is estimated to have been 6-19 billion USD globally in 2018, and in the future businesses could face huge costs if governments require them to cover waste management costs. The monetary value of losses of marine natural capital is estimated at 2.5 trillion USD annually. This is nearly five times the 580 billion USD that the global plastic market was estimated at in 2020. Cutting costs to waste management is likely just shifting the cost elsewhere.
- The problem is cumulative and persistent – in some gyres, more than half of the plastic waste found floating was produced in the 1990s or earlier.

Additional to the ocean plastic problem is the land plastic problem. Weathering of larger plastic items can produce non-biodegradable microplastics. Landfills may act as a source of microplastics [43], however with plastics in nature, microplastics produced are less contained and more likely to spread into the environment.

Microplastics may end up in soil, where they negatively affect most enzymatic activities [44], affecting organisms which live below the surface and aid soil fertility [27]. This could potentially affect agricultural output, which could negatively impact food security and economic development of areas where humanitarian aid is needed. As well as affecting soil, plastics may be eaten by livestock, which can stop milk production and harm cattle. If the cattle still do produce milk, there is risk that it will contain toxic chemicals such as dioxins [45]. Dioxins can get into eggs due to chickens ingesting soil particles [46].

Similarly, soil pollution caused by plastic waste can be injurious to higher and lower animals in the environment, damaging ecosystems [47].

Microplastics don't just pollute the seas and soil, but also the air we breathe. Although more research is needed to fully understand the health impacts of dermal exposure to and inhalation of microplastic particles, they are thought to cause oxidative stress and inflammation. Our immune systems' inability to dispose of them could potentially lead to chronic health problems. Notably, microplastics can harbour pathogens on their surface, leading to increased transmission risk [48]

It's not just ecosystems and human health. In Bangladesh, plastic waste caused blockages of drainage systems, contributing to deadly floods in 1988 [37]. In other regions, plastic waste blocking sewage systems has created breeding grounds for mosquitoes, increasing risk of vector-borne diseases such as malaria [37].

4.6 Recycling

As shown in Fig.4.2, recycling is a preferred method of waste management in the hierarchy of waste compared to discarding, landfill or open burning. As well as a method of dealing with waste by repurposing materials with economic value, recycling provides the opportunity to use recovered plastics to manufacture a new product and shift towards achieving a circular economy model. In addition, it is attractive due to the potential environmental and economic benefits it can provide. This includes new jobs for the local community to boost the local economy, a key aim of humanitarian aid agencies, Recycling also ensures the contribution to landfill and incineration are minimised.

However, reclamation of this plastic waste is simply not economically or logistically viable in developing countries. The lack of a waste management system and education on waste management makes it extremely difficult for the plastic to be recollected for recycling.

Furthermore, the demand depends on the price of virgin material as well as the quality of the recycled resin itself. The use of recycled plastics is marginal compared to virgin plastics across all plastic types due to a range of technological and market factors. Looking specifically at polypropylene, the economic viability of PP recycling is hindered by the low cost of the virgin polymer and the type of applications that use the resin. Furthermore, economic constraints do not allow the recycler much opportunity to perform costly recycling processes such as any extended separation protocol or property rejuvenation using expensive additives [35]. Recycled plastics are not commonly used in food packaging (which is one of the biggest single markets for plastics) because of concerns about food safety and hygiene standards which further reduces the market of recycled plastics. A common problem with recycling plastics is that plastics are made up from parts of more than one kind of polymer or there may be composite fibres to give added strength. Metalized PP sachets are a key example of this, and the reason they've become such a highlighted issue.

Many initiatives aim to help reduce the plastic waste problem by recycling within developing countries/ communities. They aim to locally produce something of use from the waste in order to tackle the logistical difficulty of sending this plastic to a recycling plant. This allows the creation of jobs, as well as lower effects on the environment and human health.

For example, Waste for Warmth is a project that focuses on developing small scale manufacturing capacities for shelter insulation [49]. The project is developing a small and field-friendly machine which transforms plastic waste into insulation products for warm and safe shelters. Current tests showed that their insulation panel prototype allows to reduce fuel consumption for heating by 40%. Several initiatives to recycle and upcycle plastic waste into other useful things such as insulation or other household or farming tools are also in development. The process of recycling this waste within the developing community allows for the creation of jobs and is more economical and energy efficient than the logistics of transporting plastic back to the developed countries the aid is coming from.

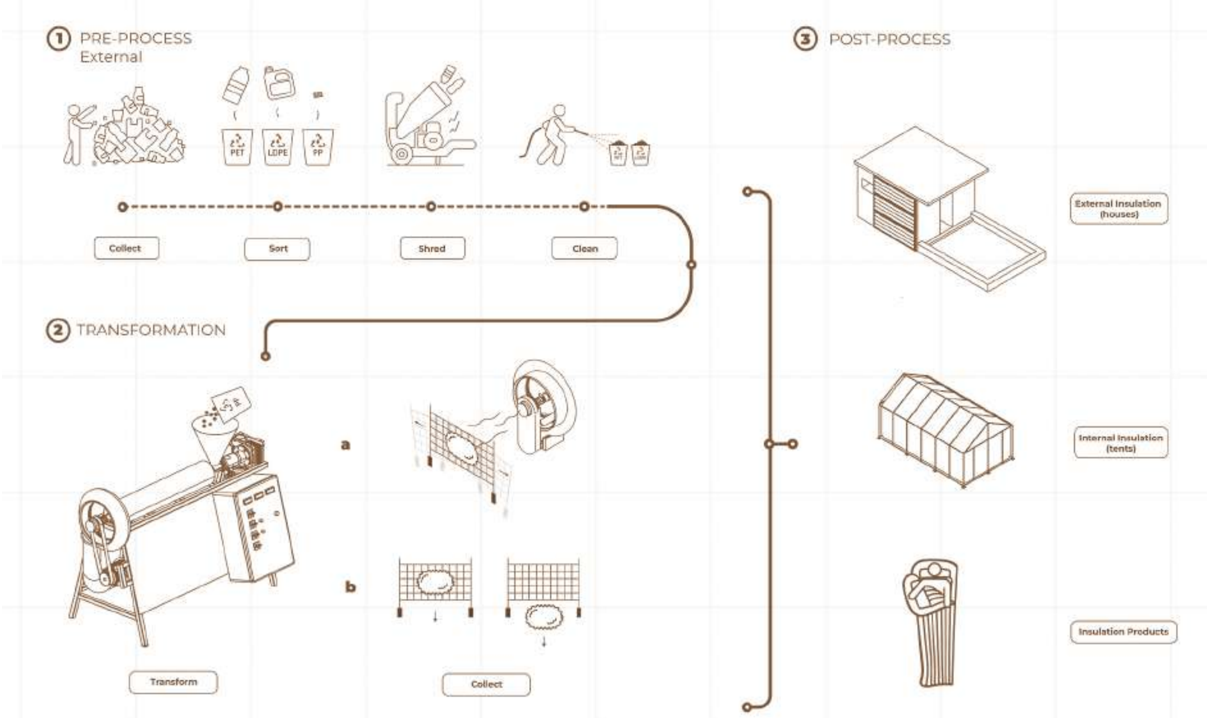


Fig.4.4- Schematic of waste for warmth program [49]

The issue with upscaling projects like these is not only lack of funding and the fact they are still in development, but also the varying environments of humanitarian aid. It is difficult to reach so many displaced communities in hostile environments with a unit that allows for recycling. Appropriate education is needed on how to operate such equipment safely and appropriately, and a degree of waste management and sorting still is needed as shown in Fig.4.4. This makes initiatives like this difficult to apply globally as many developing countries and communities will not have the means to collect & sort their waste; creating logistics within aid programs which may be difficult to manage.

4.7 Prevention and minimisation

One proposed way of avoiding use of packaging is by transporting and distributing food as a bulk cargo and using dispensing machines that allow people to the exact amount they need, when they need it, as opposed to a fixed monthly ration. This has been trialled with vegetable oil by the World Food Programme in Kenya, reducing (but not eliminating) packaging, however, requires extra care to maintain hygiene, especially during loading. This could be extended to other non-perishable and less perishable items.

The “Joint Initiative on Sustainable Humanitarian Packaging Waste Management” technical working group recommend [reference not yet available as not published]:

- Increasing the weight of product per packaging
- Increase the density of the product being transported
- Optimising secondary packaging design to reduce excess space (“headspace”), reducing the amount of material required

4.8 Conclusion

As outlined by the Fig. 4.2, uncontrolled deposits (waste that is not controlled and therefore nature is exposed to it) are the worst case scenario. Open burning of waste should be treated as uncontrolled waste in nature because:

- It releases toxic and persistent pollutants which cannot be recovered
- As the weight reduction is only 75%, the remaining plastic must still be dealt with
- The ash and other particulate matter (including microplastics) produced become waste in nature

Additionally, without any energy recovery it is not burnt in place of virgin fossil fuel, nullifying a key argument used to support incineration.

Plastic waste in the humanitarian aid sector must be treated as a disaster. Plastic pollution is creating catastrophes ranging from health issues to floods to destruction of our ocean’s carbon sinks. This view was advertised by Andrew Lamb of Field Ready – a humanitarian aid NGO – at a seminar held by the Geneva Environment Network [50].

The damage caused by open burning and uncontrolled waste in our environment is too great to allow. With destruction of natural capital caused by plastic waste being far greater than the global market for plastic (as previously mentioned), by not making a drastic systemic change we sacrifice the health of people and the environment, all in the name of the cost falling on somebody else.

As an absolute last resort, open burning should be chosen over open dumping in situations where plastic waste poses a threat to drainage systems, increasing risk of malaria, dengue fever and flooding. In other situations, open dumping should be preferred due to its lower impact on both the local and wider environment, particularly mortality rates.

The only other situation where open burning of plastic waste should occur is for medical waste and other biohazardous waste, as recommended by the World Health Organisation [51] to kill pathogens when alternatives are unavailable.

In the case of open burning, people should be educated at the point of collection that they must maintain distance from fires to avoid inhalation of toxic gases such as carbon monoxide, and it should not be done within the household.

Beyond this, the waste management hierarchy should be followed to the highest level that the situation allows.

5 Materials solutions

5.1 Introduction

The plastic bags currently used for food storage in humanitarian aid contexts are typically made from polypropylene (PP). Although technically recyclable, PP bags often are disposed of incorrectly, causing plastic pollution as they persist in the environment. Therefore, the ICRC has made a recent effort to find a replacement material with a lower overall impact [52].

Given an assumed lack of infrastructure for complicated recycling processes in a humanitarian aid situation, we propose that a biodegradable material alternative may provide the most practical and efficacious solution; no specialist training or resources are required for correct disposal [53].

To that end we have selected, from the following review of biopolymers for food packaging [54], potential materials that may be able to meet our specification for food packaging, and therefore provide a sustainable route for the future.

Hence, in this report, we first outline the properties of PP that have motivated its widespread use, and detail the issues it poses. We then explore alternative candidate materials and evaluate their suitability for food packaging, including their potential for providing an environmentally sustainable solution. Finally, we summarise our findings and suggest possible courses of action, with opportunities for future developments.

5.2 Poly(propylene) (PP)

Polypropylene is the current materials choice for food sachets, particularly in the form of films laminated with a thin layer of aluminium. The metallised polymer fulfils the strength and protection properties required for food packaging but originates from non-renewable sources and is non-biodegradable.

5.21 Production of PP

Polypropylene is produced by the chain growth polymerisation of propylene gas. The choice of catalyst strongly influences the tacticity of the resulting chains, with >97% of industrial PP synthesised in the presence of a Ziegler-Natta catalyst [55]. This encourages head to tail monomer reactions and restricts all methyl groups to the same side of the carbon chain. Catalytic control also greatly reduces the need for costly steps to remove stereoirregularities that disrupt crystallinity. The resulting commercial PP is isotactic and approximately 70% crystalline.

5.22 Mechanical Properties and Processability

Homo-polypropylene polymers are semi crystalline, with high molecular weight chains. Control over crystallinity is important, as a greater atactic content reduces strength, stiffness and melting temperature[55]. However, homo-polymers are rarely used alone due to their low glass transition temperatures (10 to -20°C), which lead to brittle behaviour as sub-zero temperatures are approached [56]. This is especially problematic when considering refrigerated conditions.

Blending homo-polypropylene with block propylene-ethylene co-polymers [57] decreases the melting and glass transition temperatures, improving the low temperature behaviour and increasing strength and ductility.

Food pouches for dry goods are constructed from oriented polypropylene (OPP) films. These are manufactured by mechanically stretching the extruded polymer using a tenter frame process shown in Fig.5.1.

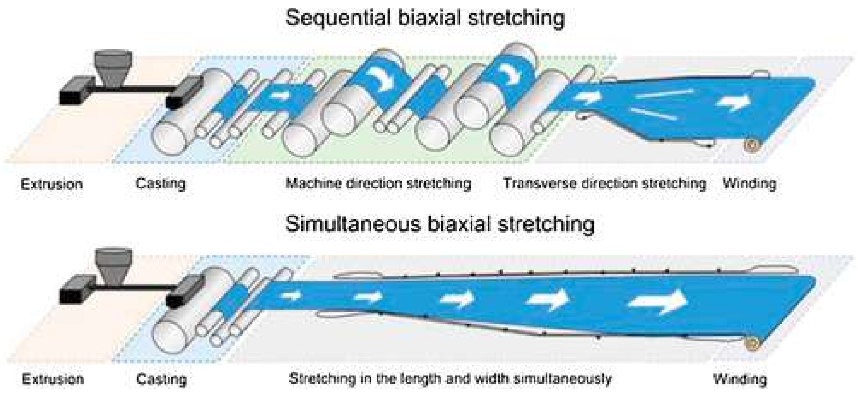


Fig. 5.1 Tenter frame process to produce OPP films [58]

Polymer chains align during stretching, increasing tensile strength to values up to 230MPa [59], four times greater than cast PP films, and over five times greater than bulk PP [60]. Consequently, required film thickness is reduced, decreasing associated material costs.

5.23 Suitability for Food Packaging

Toxicity risks associated with PP are very low, since propylene and ethylene monomers are volatile gases with low toxic potentials at ambient temperatures [57]. However, to prevent immediate oxidation degradation occurring, PP must be melted immediately after synthesis, and additives introduced [55]. Slip or antistatic agents may also be added to improve film properties [57], however are not considered a risk to health.

Polypropylene is generally considered a low-cost material [56]. It is chosen for food sachets because it has a lower density (0.9g/cm^3 [61]) than polyethylene alternatives, resulting in lighter packaging with reduced associated transportation costs. Compared to PE, PP also has higher glass transition and melting temperatures, increasing the suitability for high temperature sterilisation without deformation. PP is unsuitable for sterilisation by gamma radiation which is becoming increasingly more common due to lower energy demands. Irradiation significantly reduces strength by chain scission and crosslinking [59] and increases vulnerability to oxidative degradation.

The more major problem when considering the use of PP in food packaging is the barrier properties. PP is largely impermeable to water vapour, and stable under large temperature ranges and chemical exposure, but is a poor barrier to oxygen. This is an issue for the chemical stability of packaged food during extended storage periods. OPP films have slightly improved barrier properties, because orienting chains decreases free volume, so chains are packed closer together [62]. However, barrier properties diminish in humid environments (such as the climates of many aid-receiving countries) to the extent that increasing temperature by 10°C doubles the gas permeability [63].

Barrier properties can be significantly improved by applying a thin layer of aluminium foil to OPP films. Typical structures consist of 20μm OPP laminated with a 20μm aluminium coating. Aluminium provides a more impermeable external layer to light, water vapour, gases and microorganisms, while the internal PP layer remains inert in contact with food, and contributes strength to the packaging. The improvement in oxygen and water vapour permeabilities is presented by Fig.5.2.

	Oxygen permeability at 23°C and 50% r.h. (cm^3(STP)/ m^2dbar)	Water vapour permeability at 23°C and 85 0% r.h. (g/m^2d)
OPP, copolymer, 20μm	1800	1.3
OPP/Al	20	0.11

Fig. 5.2 Effect of laminating OPP on barrier properties [K9]

While the multilayer pouch provides a light, low-cost solution, the results in Fig.5.2 only consider bulk film properties and do not account for the effectiveness of pouch sealing. Furthermore, thin metallised layers within laminates are prone to flex cracking from mechanical stress during processing [63].

5.24 Biodegradability and Environmental Impact

Despite the suitable physical and mechanical properties, PP cannot be considered a sustainable long-term solution.

The propylene gas required to synthesise PP derives from non-renewable fossil fuel sources. Extraction of the petrochemicals is destructive and energy consuming, and natural sources are rapidly depleting. Combined with the polymerisation process, for every 1000kg PP produced, 3530kg CO_2 equivalent is released [64], contributing significantly to global warming. This does not account for the additional energy requirements or pollutants produced from processing raw PP into the final packaging.

An alternative production route is to use propanol and ethanol produced by sugar fermentation. The resulting PP has identical properties to petrochemical synthesised PP [65], so no processing modification is required, yet significantly less carbon dioxide is produced. Aside from the increase in manufacturing cost, the main problem with bio-based PP is the lack of difference in end-of-life properties to standard PP.

PP does not biodegrade, so on disposal, there are limited options for food packaging. Although pure PP is a thermoplastic, which has potential to be remelted and recycled, most food packaging consists of metallised films as described in 5.23. Separation of laminated sheets is difficult and uneconomic, so landfill and incineration are the most likely options.

5.3 Poly(Lactic) Acid (PLA)

PLA is a biopolymer deriving from natural sugar sources. While a sustainable alternative to PP food packaging, it is limited by its mechanical and barrier properties.

5.31 Production of PLA

Poly(lactic) acid (PLA) is an aliphatic polyester in the poly(alpha hydroxy) acid family. A variety of production routes can be taken, starting with different methods of producing the lactic acid (LA) monomers. Chemical synthesis is one option, yet the process is high cost, low capacity and results in a mixture of stereoisomers [60]. Alternatively, LA can be produced by microbial fermentation of carbohydrate rich substances [66]. While fermentation of pure sugars (glucose, sucrose, lactose) is simplest, the price of starting source is an important factor. Such costs are considered in Section 7. Bio-derived monomers have the added advantage of being readily available, stabilising their cost compared to petrochemical monomers, which vary in value with oil fluctuations. Highest atomic efficiency for LA production is achieved using common homofermentative bacteria (eg. *Lactobacillus delbrueckii* or *amylophilus*) [66], yet the microbial activity is heavily pH sensitive. Therefore, constant buffering using a basic solution is required to maintain fermentation. This creates a large waste disposal problem; for every ton of LA produced, 1 ton of $CaSO_4$ (gypsum) is produced [66]. Consequently, alternative pH tolerant bacteria need to be employed before this process is economically feasible. Further problems stem from microbial fermentation being a batch process. This creates a bottleneck in the PLA production process that will continue to become more detrimental as demand for bioplastic applications increases.

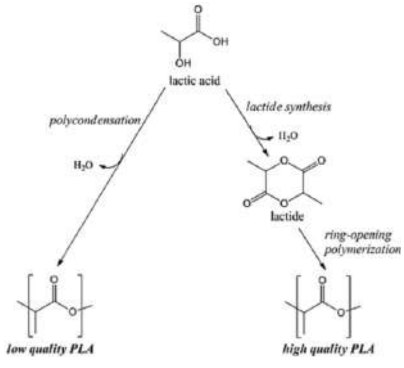


Fig.5.3 PLA synthesis routes [66]

One method of PLA polymerisation is the direct condensation of LA. High temperatures and vacuum conditions are required for the removal of water produced by the reaction. However, as viscosity increases, the removal of water becomes more difficult, so maximum attainable molecular weight is limited to only 30,000 gmol^{-1}, with many stereoirregularities. For better products, the industrial preferred route to PLA is 2 step lactide synthesis. LA is transformed to lactide, a cyclic dimer intermediate which is then converted into PLA via ring opening polymerisation. Temperatures between 180-240°C and low pressures (10-50 mbar) are required, with a 55-60% yield of PLA with higher molecular weight. However, associated energy costs are high, so alternative 1-step liquid phase processes from aqueous LA are being explored. Based on reactive distillation, the reaction occurs under atmospheric pressure and reduced temperatures (110-150°C), resulting in a higher yield (>80%) and better stereoselectivity (>99%) for a lower energy input [66].

Strict control of temperature, pressure, pH and catalysts are required to obtain desired stereochemical content; important since increasing the L isomer content increases crystallinity and ultimately produces PLA with more favourable thermal, mechanical and barrier properties [68]. This study focussed on PLA with 96:4 L:D content.

Because the properties of PLA are so heavily dependent on processing conditions, polymerisation times for synthesis are long [69]. This is a major reason the production cost of PLA is between 3.31 – 3.53 USD/kg, around 3 times more expensive than producing the current market dominator, PP (0.93 – 1.15 USD/kg) [60].

5.32 Mechanical Properties and Processability

A major advantage of PLA is it can be processed using the same equipment as conventional plastics, without the need for modification [60]. However, processes involving thermomechanical cycles (eg. multi extrusion) [68], or the fast cooling of injection moulding can lead to a loss of molecular weight by up to 40% [69]. This lowers strength and ductility, but also initiates the degradation process for biopolymers like PLA. Permeability also increases if chains do not have sufficient time to rearrange; resulting in a lower degree of crystallinity. When examining the effects of ageing, PLA exhibited reductions in strength and stiffness after accelerated ageing using UV irradiation and water spray at 50°C [69].

Compared to PP, PLA has high stiffness and low strength, with tensile strengths of 28-50MPa and elongation to failure of 7-9% [60]. Brittle behaviour is problematic when considering the suitability of replacing PP for flexible thin film food packaging, while low strength is an issue for durability of packaging. Furthermore, the density of PLA is 1.252g/cm^3 [69], greater than that of PP, slightly increasing packaging weight and consequently leading to higher fuel costs for transportation.

PLA has a glass transition temperature of 55°C and melting point of 165°C [69], demanding similar energy requirements as PP. Processing temperatures above 185°C are required, but if PLA is exposed to high temperatures for extended periods (eg. during high temperature sterilisation), thermal degradation via unzipping and chain scission occurs and molecular weight is lost. Chemical shifts and changes in peak area in ^1H and ^{13}C NMR analysis also show a change in the number of methyl groups and local molecular environment after mechanical processing [69].

5.33 Suitability for Food Packaging

The table in Fig.5.4 compares barrier properties of PLA against the currently used PP. Considering the focus of our study is the packaging of dry goods, the significant difference in water vapour transmission is a concern, and suggests PLA is not suitable for use without modification.

	Oxygen permeability at 23°C, 0-50 % RH ($cm^3\ mm\ m^{-2}\ day^{-1}\ atm^{-1}$)	Water vapour permeability at 23°C, 50–90 % RH ($g\ mm\ m^{-2}\ day^{-1}\ atm^{-1}$)
PP	50-100	0.2-0.4
PLA	15-25	5-7

Fig. 5.4 Comparison of PP and PLA barrier properties [60]

Changing molecular weight from $9x10^4$ to $5x10^5$g/mol and D-LA content from 0%-50% showed no significant change in water vapour transmission rate [69], and may alter the crystallinity [70]. This does impact barrier properties, with transmission rate decreasing monotonically as crystallinity increases from 0%-20%.

Coating with hydrophobic materials or lamination of multiple biopolymers [69] would improve barrier properties, but compromise degradation rate and result in another multilayer single use film (the problem we are trying to solve). A more viable alternative is adding nanoparticles (eg. chitosan). These reduce porosity, increasing tensile strength, and improve barrier properties as shown in Figure C [60]. However, there is a need to research further into the health risks associated with the migration of nanofillers into food.

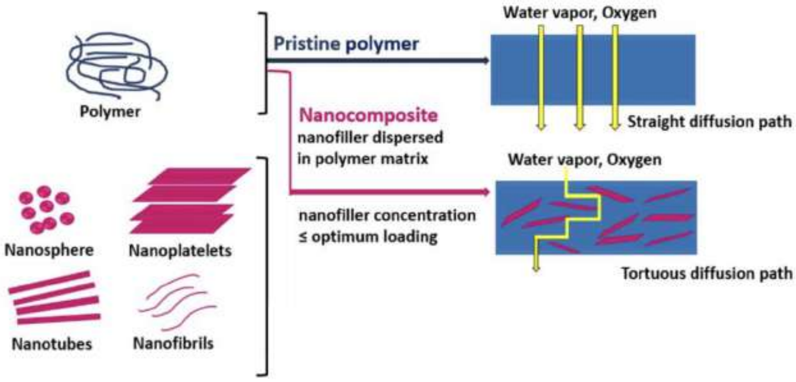


Fig. 5.5 Effect of nanoparticles on water vapour and oxygen transmission [60]

5.34 Biodegradability and Environmental Impact

Regardless of the route chosen, PLA production is shown to require up to 55% less energy than petroleum polymers, with scope to reduce this by a further 10% [69]. The bio-derived monomers and biodegradable product means climate change is tackled at either end of PLA lifespan, with the Intergovernmental Panel of Climate Change stating biopolymers have the potential to remove CO2 emissions and reduce global warming by up to 1.5°C [60].

PLA biodegradation requires 2 steps: abiotic hydrolysis of the polymer into smaller oligomers, and microbial digestion [71]. Hydrolysis is the rate limiting step, with numerous factors influencing speed of degradation. Branched PLA hydrolyses slower because methyl side groups are hydrophobic, preventing water from attacking ester bonds [72]. A lower degree of crystallinity not only improves the barrier properties as previously described, but also encourages biodegradation of PLA, since faster degradation occurs in amorphous regions. To achieve the required mechanical properties for packaging, chains should have high molecular weight, yet this increases the hydrolysis required to break chains into small enough molecules for microbial digestion, so the more naturally resistant PLA is to bacterial growth [69].

The biggest problem in PLA biodegradation is the need for high temperatures and moisture for hydrolytic degradation. Studies found chain scission at ambient temperatures [73] did not produce short enough chain molecules for microbial assimilation, to the extent that semi crystalline PLA would take decades to hydrolyse before microbes could begin to work [71]. Hydrolysis rate significantly increases for temperatures above Tg, due to increasing dielectric constant of water and chain flexibility (improving attachment of water), but this is only achievable with industrial composting; unattainable for humanitarian aid locations.

Many aid receiving countries have climates with high sunlight exposure, yet the influence of UV is still debated on the rate of hydrolysis. Some studies consider it as accelerating, as PLA becomes more hydrophilic and degradation can occur throughout the bulk, rather than limited to the surface [71]. However, other papers claim that UV degradation results in molecules that are more difficult for microbes to digest.

Microbes begin to metabolise the oligomers once molecular weight reaches approximately 10,000 Da [69], producing CO_2 and water. The actinomycetes responsible are commonly found in soil and compost [71], however, pH decreases as PLA degrades. This creates an increasingly acidic environment that denatures the enzymes involved.

Compared to other biopolymers, PLA takes a long time to degrade, making it more suitable for the long shelf-life foods we are targeting, but a balance is required such that degradation still occurs within a reasonable timeframe.

A particular recent development is the commercially available Evanesto polymer, a form of PLA containing 5% enzymatic additives. These are distributed homogeneously throughout the polymer during extrusion or injection moulding. The enzymes encourage bulk degradation at temperatures below Tg but their activity is protected during high processing temperatures. Tests executed by Organic Waste Systems (OWS) found disintegration occurred within 143 days and total biodegradation by 200 days, with no visible or toxic waste. The additive does not impact the standard packaging lifetime or mechanical properties, however, comes at a cost increase of 1-3% [74]. This appears to solve the degradation initiation issue, yet when considering lack of funding available for aid missions, hinders the suitability for the application in question.

5.4 Chitosan

Chitosan is a bio-based polymer produced from chitin, a polysaccharide found abundantly in insects, crustacean shells [75] and fungi [76]. It has, relatively recently, garnered attention for use in sustainable food packaging on account of its biodegradability, non-toxicity, and antimicrobial properties. The molecular structure of chitosan is given below.

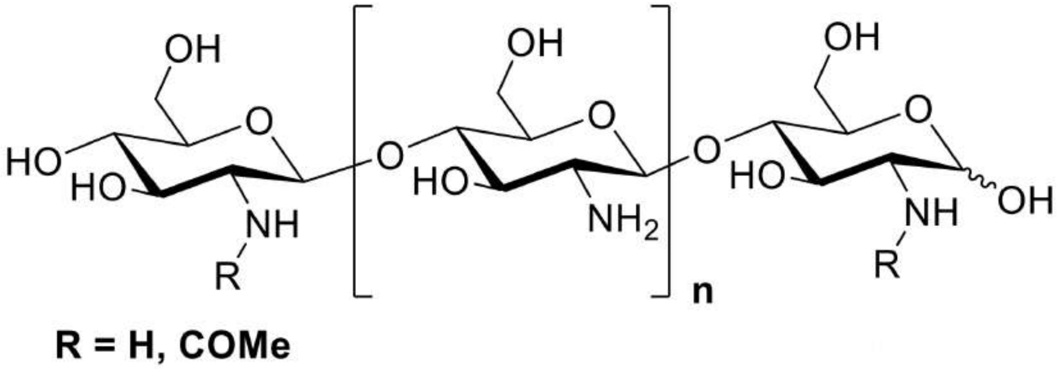


Fig.5.6 Molecular Structure of Chitosan [77]

The structure of chitosan is highly conducive to functionalisation and mixing with other materials to potentially enhance its properties, so there are opportunities for research into chitosan to produce a suitable material for packaging.

5.41 Production of Chitosan

We consider shrimp-derived chitosan, as it accounts for the majority of produced chitosan and is the source most widely used in industry [78].

Although chitosan may be extracted in several ways, it is a chemical route that has risen to prominence on account of its high efficiency, short production time and relatively low cost [75]. On a first estimation, we consider high molecular weight (Mw), high degree of deacetylation (DD) and low environmental impacts as the optimal outcome for a given method of production of chitosan, as this will lead to the most sustainable packaging with optimal properties.

Chemical extraction of chitosan from shrimp shells consists of the following steps: pre-treatment, demineralisation, deproteinization, decolourisation, and deacetylation of chitin [75]. Pre-treatment of the shells can proceed in several ways, including drying, grinding and sieving, however a simple method of washing the shells with tap water, and optionally soaking in diluted hydrochloric acid (HCl), has been proposed, demonstrated to be effective, and environmentally less harmful at producing high quality chitosan [79].

The purpose of the demineralisation step is to remove calcium and magnesium compounds from the shrimp shells to begin separating off the chitin. The shells are reacted with either HCl or acetic acid, depending on the final application of the chitosan, with use of dilute HCl (about 0.02 mol per gram of shell powder) resulting in higher quality chitosan. The reaction of HCl to remove calcium carbonate is given as follows [80]:

$$HCl + CaCO_3 \rightarrow CaCl_2 + H_2O + CO_2 \tag{2}$$

The chitin is then separated from the soluble salts left over, by filtration and washing.

Deproteinisation involves reacting the shrimp shells with a base such as NaOH or KOH to dissolve out proteins, to isolate and begin to deacetylate the chitin. Typically, NaOH has been used in a concentration of 0.002-0.09 mol per gram of dry powder, with lower temperatures, below 65°C, giving rise to more favourable properties [80]. However, use of KOH instead of NaOH is gaining popularity, particularly because potassium based by-products may actually be beneficial to the environment as a key nutrient for plants. Sodium by-products are, instead, harmful [81].

Decolourisation of chitosan is generally implemented for commercial reasons, to produce a plastic without the potentially unappealing natural brown colour. However, it may also improve the water-barrier properties of the packaging as bleached chitosan can exhibit lower water binding capacity due to an increased wetting angle on the packaging surface [82]. To achieve this, the chitin may be bleached with 30% H_2O_2 for three hours [83].

The deacetylation of chitin is the process by which chitosan is ultimately produced. There are a number of ways this can occur, and different methods will result in different DD, and therefore different properties. For industrial applications, a hot alkali treatment is often applied. Chitin is mixed with nominally 50% NaOH, stirred for 30-120 min depending on desired level of DD, rinsed in distilled water, and dried, yielding chitosan [84].

5.42 Processing Chitosan

The film-forming properties of chitosan enable its use in food packaging. Most commonly, chitosan films are produced by solution casting, for example in the following study on chitosan films for storage of butter [85]. The solution casting process occurs as follows: Chitosan powder is added to acetic acid at a nominal concentration of 2%, and stirred until the chitosan is completely dissolved. The solution is then cast onto a flat surface and left to dry at 35 °C for 48 hours, sonicated every 8 hours to aid evaporation of the solvent. The resulting film is peeled off the casting surface, washed in NaOH to remove any residual acetic acid, and finally washed with distilled water before the final drying step [86]. Although widely used in laboratory settings, and able to be easily modified to include additives, the solution casting method is not particularly suitable for mass production as it does not scale up well to industrial settings. An alternative must be explored, and it is found that in some instances chitosan films are able to be produced by blown film extrusion (BFE) which can be used on much larger scales.

The BFE process begins with plastic pellets being fed into a screw extruder to melt and then fed through an air ring into a circular die. The generated air pressure then causes the molten plastic to coat the inside of the die, essentially inflating the plastic, producing a large film up to 0.5mm thick. For food packaging purposes, the process involves coextrusion of many different polymers to produce sheets of up to 11 layers of film. A schematic of the processing equipment is given below [87].

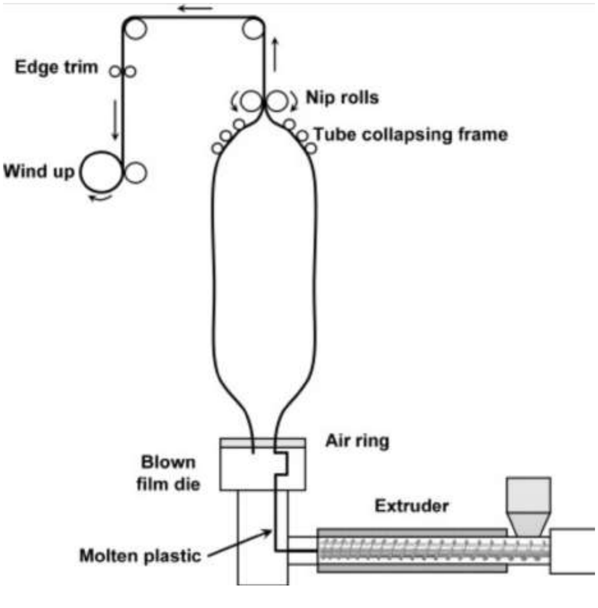


Fig 5.7 Schematic of the Blown Film Extrusion Setup [87]

For a successful BFE, chitosan must be plasticized [88]. This can be achieved by reacting the chitosan in solution with aqueous acetic acid, followed by adding glycerol, which induces a moderate amount of hydrogen bonding that reduces crystallinity without forming crosslink networks, so overall the plasticity of the chitosan and the final film is increased [89]. This process is not just relevant to the processing stages, therefore, but also has implications for the mechanical response of the film during service in food packaging. Higher plasticity corresponds to greater elongation to break, for example.

5.43 Properties of Pure Chitosan

We will now consider the important properties for food packaging, in turn, for pure chitosan.

The tensile strength and elongation at break of pure chitosan films are found to have a large range depending on DD, Mw and the acid used to form the film. Respectively, these ranges are 6.7-68.8MPa, and 4.58-117.8% [90]. Using a first approximation energy consideration, this suggests a range of energy to break (strength*elongation) of between 3.2-7.9 MJ. The water vapour permeability (WVP) can range from $8.07*10^{-13}$ - $6.9*10^{-10}$ g/m s Pa and the oxygen permeability 0.8 - 5.8 cc/m day atm [90].

Aside from its mechanical and barrier properties, chitosan is proposed as a packaging material on account of its antifungal and antibacterial properties that enable its use in so-called ‘active packaging’ [91].

5.44 Combining Chitosan with other Materials

The values for WVP are unacceptably low for use of chitosan as the sole barrier in food packaging, however improvements can be made with additives to the material. For example, use of cheap, readily available and environmentally friendly acorn extract has been found to reduce the WVP of chitosan films by 57% [92].

To this end, it is proposed that the properties of chitosan can be tailored to a particular application by its use as part of polymer matrix composite (PMC) material, rather than in its pure form. A chitosan composite may be the key to delivering a practically biodegradable material with appropriate properties for food packaging. In general, composites are used to tailor properties of materials by combining, ideally, the best of both worlds of two materials with very different properties; a simple rule of mixtures approach can be applied to estimate the final properties of the composite material with reasonable accuracy. For our purpose, the aim of a chitosan composite is to improve the tensile and barrier properties, and typically this is achieved for chitosan with nanoparticles or fibre additions.

One of the most promising materials to combine with chitosan is cellulose [D]. As particles, cellulose can be added to chitosan as bacterial cellulose nanocrystals (BCNC), a biodegradable material with UV blocking properties [93]. Addition of BCNC to chitosan films up to a 6% concentration has been found to reduce WVP of chitosan by 30%, and increase tensile strength by 65%; this creates a film with tensile strength of 35MPa and elongation to break of 25% which we deem acceptable for food packaging purposes. Tensile strength can be improved further by decreasing the concentration of BCNC to 4%, an effect which may be explained by aggregation of the particles [94]. A similar effect of particle aggregation explains why there is a limit to the reduction in WVP of films by adding nanoparticles, as shown in Fig 5.8.

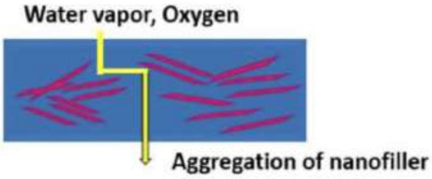


Fig 5.8 Aggregation of composite particles and fibres increases permeability [60].

Cellulose nanofibrils have also been added to chitosan, and the effect of also adding citric acid has been studied, to create a chitosan-cellulose nanofibril composite (chitosan-CNF) [95]. It is found that adding 20% nanofibrils to pure chitosan increased the tensile strength to 54MPa. However, the hydroxyl groups in chitosan and CNF, which contribute greatly to the poor water barrier properties, can be modified by crosslinking by adding citric acid, and this is found to reduce water vapour permeability to 1.40×10^{-6} g/pa s m^2. Although adding the citric acid reduces the tensile strength slightly to 43MPa, this is still acceptable for packaging applications and so this is an extremely promising possibility for a sustainable food

Aside from composites, chitosan has also been blended with PLA, showing promise by improving on the properties of both materials by creation of a nanocomposite that features both better mechanical and barrier properties [96].

5.45 Environmental Impact and Biodegradability

The biodegradability of chitosan is straightforward - it degrades completely in soil within two weeks, leaving no trace in the environment [97]. It is possible, therefore, by blending with another natural material to create packaging that, upon discarding into the environment, degrades entirely with ostensibly no negative impacts. The effects of nanofillers and blending materials are varied, complex and we have already discussed the fact that the effect of nanoparticles on the environment is not currently well understood. However, combining chitosan with another biodegradable material like cellulose provides a promising route to a material with better properties than chitosan that remains environmentally sound.

Considering a life cycle assessment of chitosan compared to PLA and PP, it is found that the chitosan-CNF composite has the lowest global warming potential (GWP), with PLA actually being the highest. The greatest contribution to the GWP of the chitosan is the solution casting process, which again appears as the limiting factor, highlighting the importance of developing a chitosan-based material suitable for processing by BFE. However, especially when considering the biodegradability of the chitosan-CNF, it is clear that a chitosan-based material has extremely high potential for reducing the environmental impacts of plastic food waste [98]. This is presented in Fig.5.9

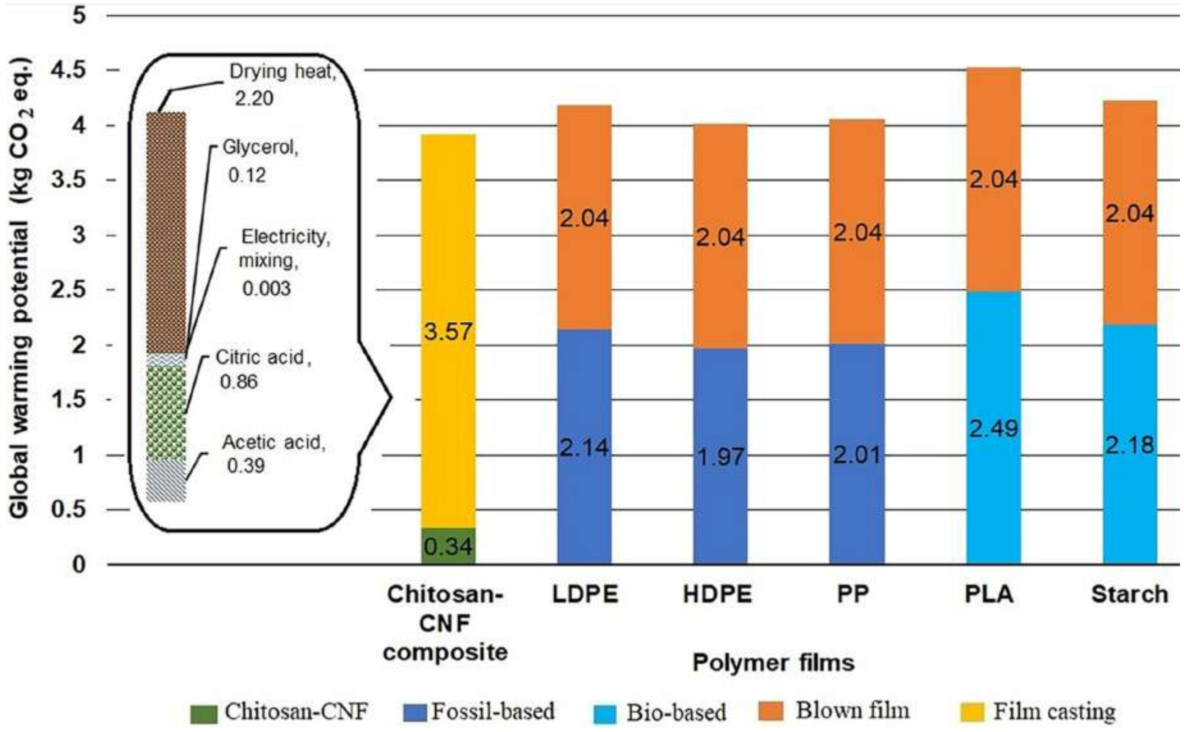
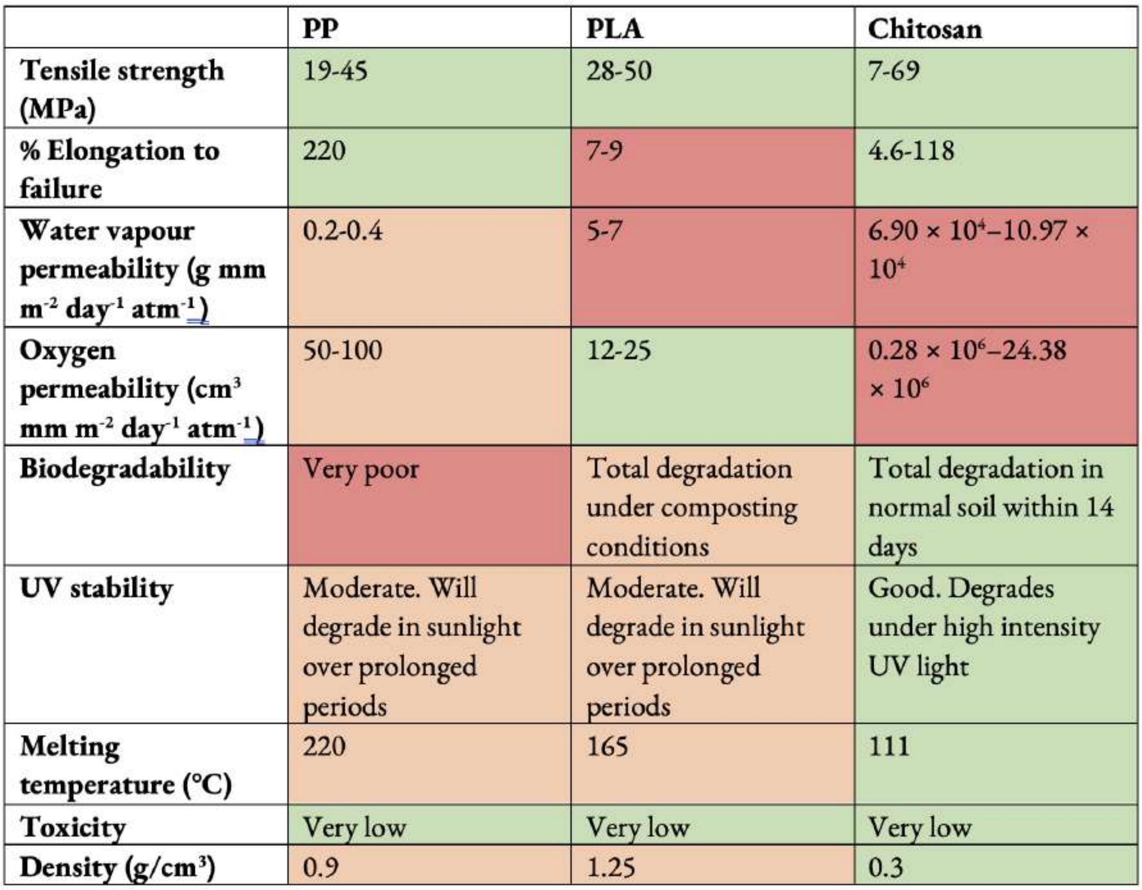


Fig.5.9 Comparison of Global Warming Potential of various plastics including Chitosan-CNF [98]

5.5 Summary and Conclusions

(JH) PP is currently the major food packaging material due to its favourable mechanical properties, cost, and ease of manufacturing. Fig.5.8 summarises key data comparing PP to PLA and Chitosan with respect to several of the specification criteria of Section 3. PP's lack of recyclability and biodegradability leads to the demand of a more sustainable packaging plastic, which is why PLA and chitosan have become our candidate materials. More investment is needed to make the degradation of PLA a viable solution - in its current form, it's simply not practical.

(JM) Chitosan inherently exhibits biodegradability in a very practical sense, although its limited processability and poor barrier performance restrict its utility; pure chitosan films are not suitable for mass produced food aid packaging. Further research will be necessary to scale up the production of a chitosan composite, perhaps incorporating cellulose, that exhibits the required mechanical and barrier properties necessary for food packaging, and sufficient plasticity for mass processing. Such a material could provide the most sustainable long-term solution.



	PP	**PLA**	**Chitosan**
Tensile strength (MPa)	19-45	28-50	7-69
% Elongation to failure	220	7-9	4.6-118
Water vapour permeability (g mm m^{-2} day^{-1} atm^{-1})	0.2-0.4	5-7	6.90×10^4–10.97×10^4
Oxygen permeability (cm^3 mm m^{-2} day^{-1} atm^{-1})	50-100	12-25	0.28×10^6–24.38×10^6
Biodegradability	Very poor	Total degradation under composting conditions	Total degradation in normal soil within 14 days
UV stability	Moderate. Will degrade in sunlight over prolonged periods	Moderate. Will degrade in sunlight over prolonged periods	Good. Degrades under high intensity UV light
Melting temperature (°C)	220	165	111
Toxicity	Very low	Very low	Very low
Density (g/cm^3)	0.9	1.25	0.3

JH - Fig.5.8 Comparison of PP,PLA and Chitosan properties. Data sourced from [57], [60], [61]

6 Business approach

6.1 Economic change to resolve the crisis

A brief introduction to sustainable thinking to guide an alternative business approach

6.11 Linear Economy - Productivity over sustainability

The current use of plastic waste is a clear example of a linear economy. A linear economy is based on the principle of 'take, make, dispose' [99], seen in Fig. 6.1 [100]. Plastic is produced for single-use in food packaging and then discarded or incinerated. This approach leads to extracting raw materials faster than they are replenished, depleting natural resources. In disposal, the waste causes health, emissions and storage issues from both incineration and landfill, as discussed in Section 4. In a humanitarian context it is essential to maximise output, and the linear economy does this to the detriment of the environment. 'Value is created in this economic system by producing and selling as many products as possible' [101].

Fig. 6.1 Linear economy graphic [100].

6.12 Circular Economy - Maximise resources, minimise waste

A circular economy 'emphasises the elimination of waste by extending or expanding the usability of resources' [102]. It epitomises UN Sustainable Development Goal 12 of ensuring sustainable consumption and production patterns. To resolve the plastic waste crisis it is essential to adopt a circular model. This is more than just a modification to the linear model but requires systemic change where we must both reuse resources, and reduce production and waste, "bringing the edges in" [99].

The challenge is to implement these changes in an effective manner, whilst addressing human needs. 'This can provide a way to not only protect the environment, but use natural resources more wisely, develop new sectors, create jobs and develop new capabilities' [103].

Fig.6.2 Circular Economy graphic [102].

A circular economy can be broken into four steps, each providing 'an opportunity to put the materials back into productive use' as seen in Fig. 6.2 [102] .

To achieve this, products are eco-designed with their end-use in mind from the start - to be 'repairable and built to last' or degradable back into raw materials [99].

The wider social context means we must consider how we can adopt this model and eco-design to avoid the wastage of single-use packaging and promote recycling [99].

6.2 How to go forward?

To transfer these concepts into a business setting, the following sections consider:

Who is our consumer? What is a suitable business approach and model? Is this approach feasible?

This gives a brief description of the developing approach to business in the humanitarian sector and considers relevant examples.

6.21 Changing business approach

In the context of our project and consideration of materials solutions, our only consumers are humanitarian agencies, or governments. Options for investment funding include for all funding to come through donations and grants, or some private involvement and working for profit.

There are compelling reasons for private sector investment in humanitarian aid. 'Private sector is more efficient, brings new capabilities, is better at managing risk, and has a more sustainable response model' [104]. This drive has been exacerbated by the COVID pandemic, and has led to a lack of growth in humanitarian assistance, coinciding with an 'all-time peak in people needing humanitarian assistance' [105,106]. There is a humanitarian funding gap, and private sector investment is a solution.

Alongside this, donor funding has shifted to being on a 'payment by results' basis, rather than by grants [104]. Non-government organisations, NGOs, generally cannot absorb these types of risk as they do not have the reserves of a profit-making company. This is why a more diverse funding model is attractive. Such an approach with more constant funding can offer a better response to emergencies and lower overall costs, as found in a study funded by UKAid [107].

The greater investment that working for profit can provide would allow for more research into materials solutions, and the infrastructure needed for their implementation. This must be offset by the risk of fluctuating supply and demand and logistical complications of working in humanitarian aid [108]. There is no perfect solution, however there is evidence it could be viable and beneficial, as shown in Section 6.24.

In summary, it is recognised that private investment is the next step in improving humanitarian aid, and in Section 5 we saw materials solutions are the next step for plastic waste. Implementation in combination may help remove the barriers to implementation.

6.22 A suitable business model

Social business/enterprise - A Type One social enterprise is defined from the works of Muhammad Yunus as: 'A business which is non-loss, non-dividend, and investor owned. It solves a social problem and is owned by investors who reinvest their profits in expanding and improving the business' [109]. They combine 'commercial success with real social and environmental impact', and so present themselves as exciting opportunities for investors [110].

Given the context of humanitarian aid, and the benefits of working for profit, a social enterprise seems a good solution. What is the advantage over a for-profit company? Social enterprises offer a social and environmental appeal to investors and have different priorities. 'Profit is just a tool to fulfil the social enterprise's social mission' [111]. This is an important sentiment in the humanitarian sector, and crucially promotes change towards the circular economy from the value-driven linear economy.

6.23 Is this approach feasible?

From a financial perspective it is clear that countries around the world recognise the crisis, with $165 billion total spent on aid in 2014 [112]. Of this, less than 6% was spent directly, the rest was spent on contracts with NGOs, UN and private contractors [112]. This would indicate that there is a market for our business and other solutions to the crisis.

A key barrier to implementation of new technologies in this field remains the ability to secure funding, despite the volume of contracts available [A,C]. As a result, cost must be optimised. Section 7 considers this limitation.

To understand how to do this and help answer the key questions posed we will consider suitable case studies and published reviews, Sections 6.24, 7.1.

6.24 Case Study - An example of successful private investment in the sector. From *The humanitarian cost of plastic waste* podcast [113]:

IFC, a member of the World Bank Group, has worked to issue a "Blue Bond" for approximately 300 million dollars; this is a bond whose proceeds go specifically to keeping our oceans blue by supporting recycling investments [113]. This is the 'first-ever blue loan to a global plastic resin manufacturer' [114], Indorama Ventures, a plastics manufacturer recognised with several sustainability awards [115]. The funding is aimed at recycling 50 billion PET bottles a year by 2025 in areas suffering from mismanagement of plastic waste [113].

On the loan, the IFC Vice President for Asia and Pacific said, 'This blue loan complements IFC's ongoing work on a circular economy for plastics and enhanced waste management in Asia. It demonstrates that recycling can be an effective intervention to address plastic waste while supporting our overall sustainability and climate change agenda' [114].

This ties together the discussion of the economics of humanitarian aid, and our business approach. It supports the importance being placed on change to a circular economy, the drive for private investment in the sector and the feasibility of financial support for a technological solution to reduce plastic waste.

7 Financial viability

To assess any material solutions there are financial questions to consider. This will help give an overview of ways forward relative to the solutions that have been discussed, an idea of why these solutions are not currently occurring, and how and why this might change.

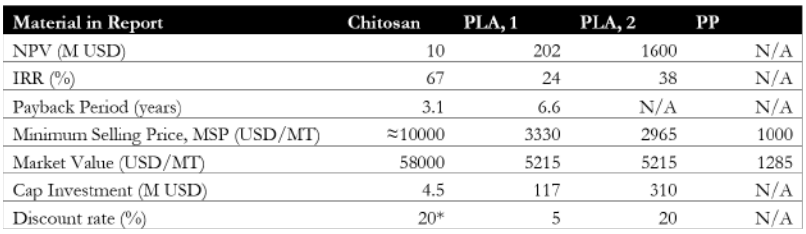
7.1 What investment is needed to establish production? How will the new packaging compare in price to existing packaging?

A Literature Summary

A number of reports were reviewed and summarised but it was not possible to find studies pertaining to the case of humanitarian aid within the timeframe of the project.

Estimates and comparisons between solutions are based on these sources, each having advantages and issues. The available reports relate to selling the produce commercially. For humanitarian purposes it is assumed the solutions will show the same relative relationship. An evaluation will then be made using the key data from the reports.

Metrics from the papers are summarised in Fig.7.1. A summary of the context of the papers then follows. The calculations and abbreviations involved in constructing a discounted cash flow analysis will not be discussed here and can be found online [116].



Material in Report	Chitosan	PLA, 1	PLA, 2	PP
NPV (M USD)	10	202	1600	N/A
IRR (%)	67	24	38	N/A
Payback Period (years)	3.1	6.6	N/A	N/A
Minimum Selling Price, MSP (USD/MT)	≈10000	3330	2965	1000
Market Value (USD/MT)	58000	5215	5215	1285
Cap Investment (M USD)	4.5	117	310	N/A
Discount rate (%)	20*	5	20	N/A

Fig.7.1. Table of discounted cash flow analysis data [60, 117,118,119,120,121].
*Estimated from data in report [117]

7.11 Chitosan

Riofrio et al give a summary of several financial assessments of Chitosan. The analysis is based on deriving 110 tons of Chitosan from 5000 tons of shrimp waste. The Ecuador-based project is based on a 10-year production cycle and 2 year investment period. They also considered the lower cost option of chemical production of chitosan, as in Section 5.41. The capital investment necessary is approximately 4.5 million over 3 years [118].

The study findings appear robust and the economic analysis based on NPV and IRR is very promising for an appropriate discount rate, however this is based on commercial production. The analysis produces a MSP value, which is more relevant for comparison [118].

Riofrio et al also considered a comparative study in Spain, which produced similar results, supporting the validity of the estimates made for Ecuador [118].

This report is particularly useful in its scale, representing a level of investment that is suitable to be taken up in the developing field of materials solutions.

7.12 PLA

Two papers are considered to give an idea of the economic assessment of PLA, through its various routes of production:

In "PLA 1", Kwan et al present an assessment of PLA in an environment with well-developed and ideal infrastructure. It considers conversion of food waste to PLA, a wholly alternative production with lower raw materials costs, with a capacity of 10 metric tons per hour with a 20-year lifetime [119].

"PLA 2" considers the various ways of producing PLA, using sugarcane, waste and a combination. Ratshoshi et al consider these production scenarios and the infrastructure involved, each with variable costs of raw materials and processing. Capacities in the range of around 300 metric tons per hour with a 25-year lifetime are used. It is found that the route that is financially preferred is a combination of waste usage and sugarcane use, and this data is featured in Fig.7.1. Minimum selling rates for PLA 2 were slightly lower, supporting the conclusion that the combination route is preferred. Other metrics follow this trend [120].

In combination the two papers give a more reliable idea of the potential of PLA production despite differences in infrastructure, and a clear idea of the financially optimal production route.

From the market price and MSP, the findings of both papers suggest feasible investable projects with enough of a margin that humanitarian use could be possible.

The disadvantage of these papers is that their scaling is much greater than for Chitosan and so may be less applicable in the context. This scale is seen in the Capital Investment Values.

7.2 Financial summary of solutions

7.21 PP

The current production cost of PP is around 1000 USD/MT [60]. This makes it cheaper than the biopolymers considered.

PP is more economic to produce because the manufacturing infrastructure is widespread, optimised and at an economic scale. This cost benefit is exacerbated by the investment in infrastructure needed for alternative solutions.

There are clear financial reasons to transition away from PP-based packaging including the introduction of eco-taxes on non-recyclable packaging in the UK and EU. This could promote a change to alternative solutions, or more localised production.

Another benefit of moving to biopolymers is that it removes the costs of plastic waste handling. This cannot be readily quantified given the infrastructure of areas receiving aid but is an additional cost in use of PP beyond production that must be considered.

7.22 Chitosan

The key disadvantage of Chitosan that can be seen from Fig.7.1 is the MSP. Chitosan appears a great investment for commercial profit given the ratio of Market Value/MSP, however a humanitarian agency is unlikely to be willing to pay over ten times as much as PP.

The reason for Chitosan's expense is the manufacturing costs, given the multi-step processing required. Riofrio et al discuss the possibility for reuse of reagents that could reduce cost, which might address the MSP discrepancy and make the process financially viable. It is suggested that in the model in Ecuador 'variable cost counts for 60% of manufacturing costs', so scale-up will significantly reduce costs [118].

The high potential profitability seen could indicate that this investment will come from commercial interest and then the field could be taken up by the humanitarian sector.

This analysis has considered the use of pure Chitosan; composite uses require further research.

7.23 PLA

PLA is more realistic in the short-term than Chitosan. The MSP is around three times that of PP, and sale price to humanitarian agencies could realistically be in the region of four times. PLA has higher manufacturing costs than PP because polymerisation times are long, and the process is more energy intensive based on high temperatures and vacuum conditions. A similar argument as for Chitosan can be applied, that costs would be reduced as the process is perfected.

The main issue with this analysis of PLA is how costs would scale to an investment such as that of the Chitosan report. It was not possible to confirm this within the research time available, but it would be expected that the MSP would rise, so a balance would need to be found between investment scale and a selling price for humanitarian agencies. This and the profitability suggested by the reports support the prospect of private investment. with production split between commercial and humanitarian use. This model is seen currently by companies such as Mondi [121], a high-profile recent case. This is beyond the scope of the report but could be a point of interest for future work.

This purely financial consideration of the different materials solutions to the plastic waste crisis gives more context to the possibility of their use. Reviewing relevant literature allowed comparison of solutions and insight on the potential ways forward. It is important to recognise that this is a developing field in a sector that is often hard to quantify. More refined research is needed before any conclusive judgements can be made or solutions implemented.

8 Conclusion

Not enough humanitarian agencies have considered materials solutions to plastic pollution in humanitarian operations. From the TGW run by the Joint Initiative for Sustainable Humanitarian Assistance Packaging Waste Management with 50+ participants, only 1 other person was investigating materials solutions[B]. Similarly, not enough biodegradable plastic research explores the problem within the frame of humanitarian aid.

A significant amount of plastic waste generated by humanitarian food aid comes from PP bags and metallised laminated sachets. PP's persistence in the environment poses substantial health risks to land and marine life alike as it does not degrade and may release harmful particles into the environment. We have considered incineration as a waste management method and found that the resulting greenhouse gases and harmful emissions reach unacceptable levels. Other initiatives for waste management help mitigate the impacts but require resource and time intensive proprietary research for each disaster stricken region and are not easily deployable. As such, most recycling schemes in refugee camps fail due to logistical and labour management problems. Recycling schemes can be valuable in relatively stable regions where existing waste is an issue and ecosystems are understood with favourable implementation strategies. To sidestep the logistics and politics problem, a materials solution that works in all environments has to be found.

Materials solutions have typically taken up to many years to realise. However, with a long term view, dedication to the exploration of the process, structure, and property space and use of high-throughput screening and materials informatics techniques, many current candidate materials can be accelerated through the development to implementation. Closer to fruition is PLA, as costs have already been reduced to near-acceptable levels although PP still remains a cheaper material and so we stress the massive environmental benefits that PLA has, which may lead to cost savings in the future. PLA is a versatile material that is also used in cardiovascular implants, tissue engineering and personal protective equipment (PPE). Investment into research to commercialise PLA in plastic packaging will aid in the development of other biodegradable materials that will improve polymer manufacturing in related plastic industries benefiting economies as well as regions in states of emergency. Chitosan, a bioengineered material, presents exciting opportunities for the long term as it is significantly more biodegradable than PLA and is more conducive to modifications and blending allowing for the manipulation of its properties. As a result, with significant investment of time and money, chitosan may, in the future, provide a holistic solution to PP bags and use of PP in metallised laminate sachets, having the potential to feature the crucial mechanical, barrier and food-safe properties required, advancing polymer materials science and creating sustainable humanitarian aid for those that need it most.

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