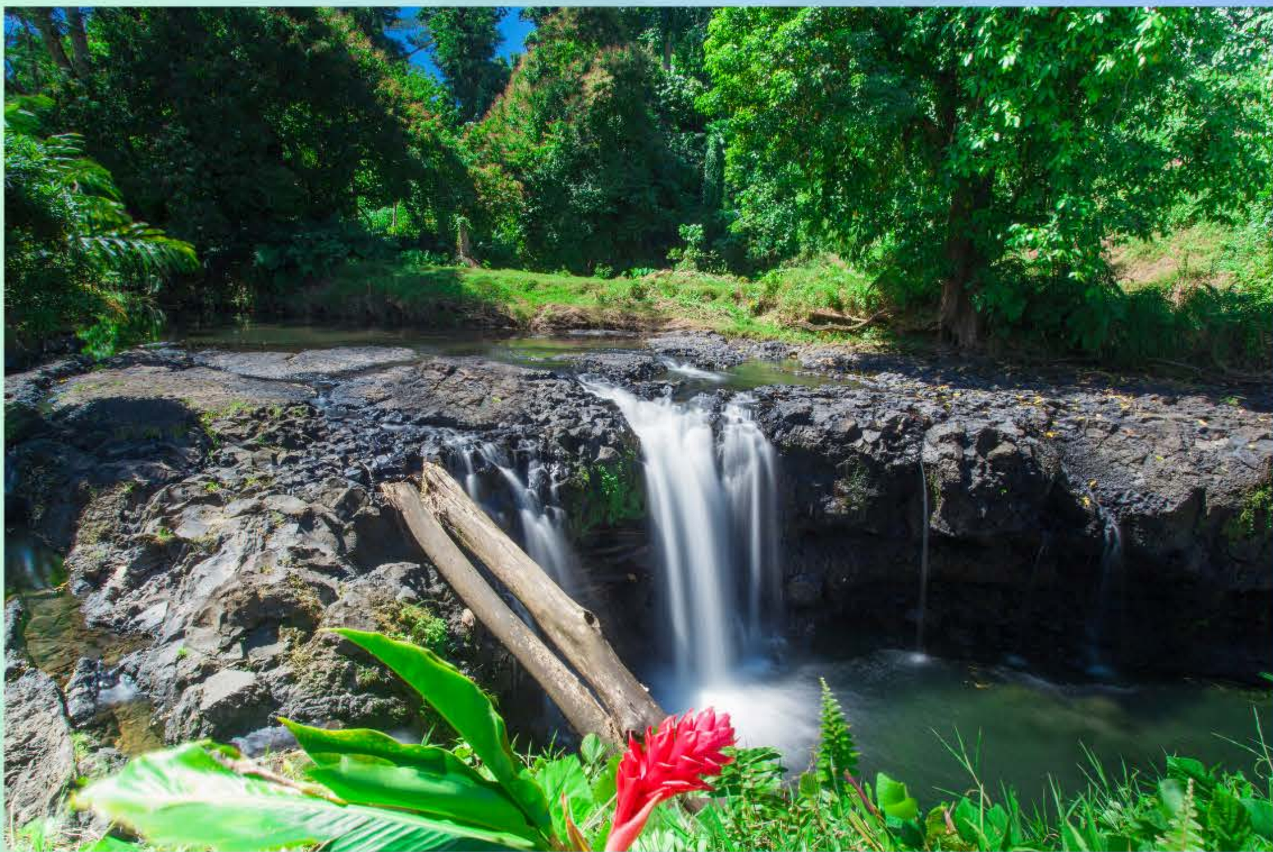
PACIFIC OCEAN LITTER PROJECT

Feasibility Study of Implementing PHA Production in Samoa



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Acknowledgment

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Faafetai tele lava.

Abstract

This study explores the potential of polyhydroxyalkanoate (PHA) processing in Samoa as a sustainable pathway for waste management and economic development. With increasing global concerns over plastic pollution and the urgent need for sustainable alternatives, PHA emerges as a promising biodegradable polymer. Samoa, like many other small island nations, faces challenges in waste management and environmental conservation. Leveraging its biomass resources, policies, and community engagement, Samoa could harness PHA production to address these challenges while creating socio-economic opportunities. This preliminary study investigates the feasibility, benefits, and challenges of PHA processing in Samoa, highlighting its potential as a catalyst for sustainable development.

Introduction

This was study was a qualitative data based research study which consisted of conducting literature reviews, surveys and interviews over the course of six months from August 2023 to January 2024. The purpose of this study was to assess Samoa's capacity to produce bioplastic alternatives to the current plastics, as single use, foams, and other plastics bans are currently in implementation. As well as, to promote circular bioeconomy approaches and implementation of a PHA (polyhydroxyalkanoate) production facility using waste biomass.

PHAs are biodegradable polymers synthesized by various microorganisms as energy storage compounds. They are produced from renewable resources such as sugars or fatty acids through microbial fermentation. PHAs have gained attention as eco-friendly alternatives to conventional plastics due to their biodegradability, compostability, and potential for sustainable production. These properties make PHAs promising materials for addressing environmental challenges associated with plastic pollution and promoting a more sustainable future.

In Samoa, the Waste Audit Report 2021 states that 27,057 tonnes of waste is generated yearly, and the waste generated exceeds the amount that is actually reaching the landfills. Even so, with the landfill's current capacity it still cannot accommodate all the waste it is receiving and will require an expansion in the near future. It is reported that the mismanagement of plastic waste from the region accounts for 2.7 of the 12.12 million tonnes of plastic filling the oceans every year and only 64 percent of plastics make their way to landfill, 24 percent are being reused at least once, while remaining 12 percent of plastics are burned, used outdoors in some way or dumped in a backyard landfill.

This is why initiatives to ban single use plastics and implement environmentally acceptable approaches are crucial for the safeguarding of our environment, as the decomposition rates cannot compete with the waste generation rate. This study looked into the different aspects that both determine the practicality of PHA production in Samoa, as well as each component that will be required for a successful implementation. To achieve this, a thorough understanding of technical, economic and operational aspects of PHA production, ascertain the feasibility of establishing a production process, identify potential challenges and opportunities, and ultimately make an informed decision regarding the viability and potential success of investing in PHA production which will be discussed in this report.

The PHA Feasibility Study initiated under POLP to assess Samoa's capacity to provide bioplastic alternatives to its current plastics (single use and foam bans currently in implementation as well as other plastics) through circular bioeconomy approaches and implementation of a PHA (polyhydroxyalkanoate) production facility using waste biomass. Ultimately, the study sought to produce a report enabling potential donors as well as local government and policy makers to understand the potential for PHA production from waste as a bioplastic substitute for petroleum plastics, in order to contribute towards a circular bio-economy in Samoa and the key factors likely to impact on a successful implementation.

Samoa has recognised its dependence on primary industries and tourism while suffering from a lack of manufacturing industries. A waste to energy strategy has been initiated whereby coconut residues are converted to electricity via biogas in a proposed new facility. A 'waste' to electricity operation in Samoa is a biomass gasification plant has been set up near the international airport and commissioned in 2020. Based on data provided by SOSAF 2015 (Situation and Outlook for Samoa Agriculture and Fisheries), 1 published by the Samoan Ministry of Agriculture and Fisheries, an expert group at the University of Queensland has estimated that solid coconut waste is at least 56,000 metric tonnes per annum. Additionally, significant agricultural waste is produced by banana and cocoa crops, as well as by invasive creeping plants threatening agricultural production.

Despite many initiatives by the government, Samoa has a significant refuse problem, and more needs to be done to maintain the pristine beaches and the natural good water quality. Processes exist to produce the naturally occurring biopolymer PHB (one of the bioplastics belonging to the PHA family) from surplus biogas that is economically competitive with conventional petroleum-based plastics, as well as other PHA polymer types from fermentation of organic biomass. PHAs are completely biodegradable eliminating threats to the environment through human behaviors. However, through a concerted effort by relevant research institutions such as SROS to support the switch to a circular bio-economy in Samoa will facilitate the creation of highly qualified jobs in new sustainable industries and many others in the wider agricultural sector.

Study Objectives

Following objective scope will explore the technical, economic and operational aspects of PHA production including current market demand for plastics, resource availability, production methods and technology. The ultimate goal is determining whether the PHA production is feasible and sustainable for Samoa.

1. Determine the need for Polyhydroxyalkanoates (PHA) by comparatively assessing the rates and volumes of single use plastic importation in Samoa
2. Investigate resource availability as potential feedstock for PHA production and identify compatible green waste technologies suitable for Samoa
3. Explore existing social, regulatory policies and regulations regarding waste generation and more importantly the disposal of green waste. As well as, looking into communal attitudes that may contribute to the use of petroleum-based plastics and how this can be influenced into the potential acceptance of ecofriendly alternatives
4. Provide a holistic view of PHA production for Samoa and recommendations for realistic implementation

1. Single Use Plastic Importation in Samoa

The scope of this section is to assess public records on import and export data of single use plastic (SUP) as well as utilize a qualitative approach through interviews with local companies importing and exporting plastic products. Specifically, the information sought are:

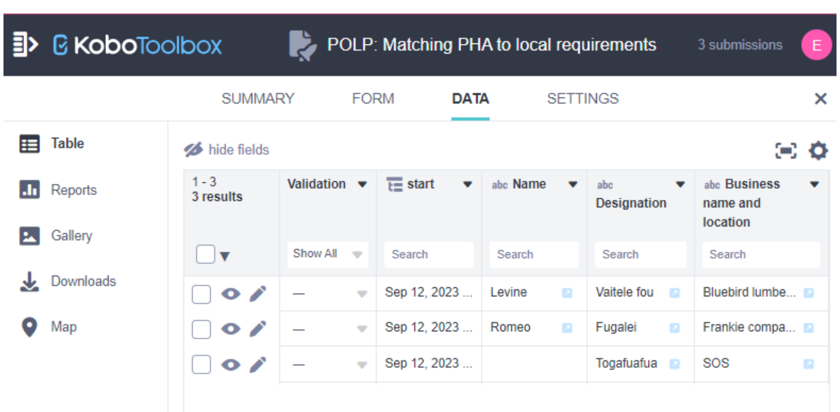
1. Volume and types of plastic imported into Samoa: followed by close scrutiny of SUPs
2. Uses and technical requirements by each application (focusing on top 80% volume)
3. Local vs export applications
4. End of life scenarios within Samoa
5. Future requirements based on changing social perceptions of plastics.

Due to the wide range of plastic polymer products available in the country, the focus of the study will be on SUP products as the potential stream for substitution with PHA.

1.1 Data Collection and Processing

In order to assess the application of plastics and the social perception of their use, the methodology used in this study was a combination of quantitative and qualitative measures. This involved both desk-based research and interviews with local enterprises that are significantly engaged in the movement of plastic commodities. The staff of SROS sought Samoa-specific information to ascertain the level of available knowledge and made arrangements for interviews to be executed on-site.

The Ministry of Customs and Revenue in Samoa and the Bureau of Statistics in Samoa were contacted for information. Interviews with a number of major distributors of plastic products with a set of questions aimed at the stated objectives were scheduled. And in person interviews were conducted using the KoboToolbox application to gather findings. In cases where information was not available or missing, assumptions were made and duly identified as a potential area of risk.



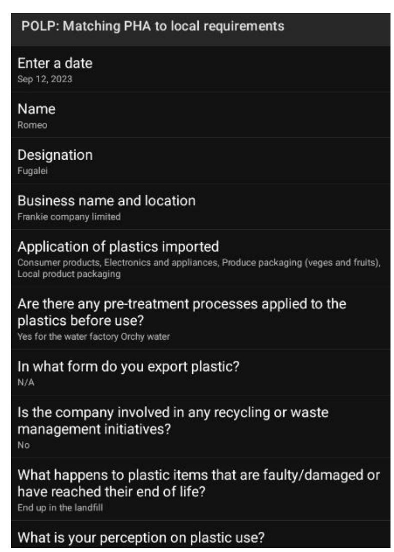


Figure 1. Screenshots of KoboToolBox used for interviews

Data on top importers of target SUPs was attained from the Ministry of Customs and Revenue whereas import and export datasets on weights of the SUPs was from the Samoa Bureau of Statistics. The data from MCR allowed us to select the businesses to interview while import and export data from SBS was analysed for trends. Both sources supplied the datasets in weight (in metric ton) and were sorted using the Harmonised System Code (HS Code) for tariffs. As a result, exact volumes on specific targeted SUPs imported was not available thus the data presented is a rough representation of our target products. Going forward, the specific plastic products of interest, which may be potentially substituted for PHAs, will herein be referred to the classification label according to HS Tariff Codes.

Table 1. Targeted plastic products with descriptions and HS Codes.

Target SUPs	HS Section	HS Code	Classification
Plastic cutlery, Plastic plates and cups	**3924.0000**: Tableware, kitchenware, other household articles and hygienic or toilet articles, of plastic	3924.1000	Tableware and kitchenware
Food containers and lunchboxes, Plastic packets and wrappers	**3923.0000**: Articles for the conveyance or packing of goods of plastics: stoppers, lids, caps and other closures of plastics	3923.2900	Of other plastics
Water bottles		3923.3000	Carboys, bottles, flasks and similar articles
Plastic bags		3923.2100	Of polymers of ethylene

1.2 Imports

Five years (2018 – 2022) of imported plastic data was assessed with the focus being on the targeted SUPs and this is presented in Table 2. From this, Figure 1 presents a clear trend of the demand of SUP products in Samoa.

Table 2.Total weight (metric tons) of targeted SUPs imported from 2018-2022 by HS Code classification. Data sourced from SBS

Year	Weight (metric tons)			
	Of polymers of ethylene	**Of other plastics**	**Tableware & kitchenware of plastics**	**Carboys, bottles, flasks and similar articles**
2018	684.20	3280.0	900.10	303.37
2019	182.05	176.49	541.13	385.21
2020	103.18	107.94	275.71	263.12
2021	162.75	183.66	435.86	354.32
2022	252.79	380.41	400.88	388.63

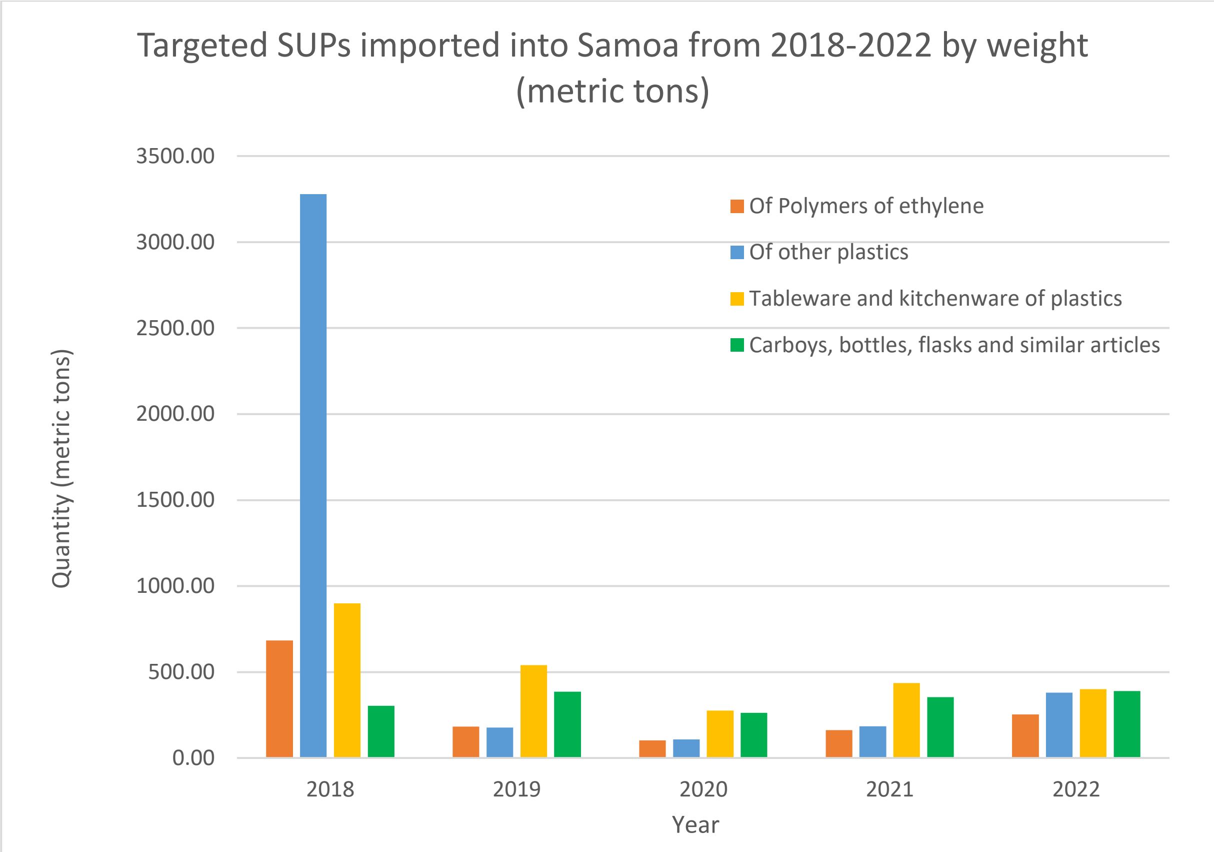


Figure 2. Targeted SUP's imported into Samoa from 2018-2022 by weight. Data sourced from SBS

Prior to COVID-19, the imported weights for the focused class of SUPs was the highest in 2018 compared to the other years with the exception of "carboys, bottles, flasks and similar articles". In particular, "other plastics" which includes, but is not limited to, food containers and lunchboxes, plastic packets and wrappers was the anomaly standing at more than thrice the weight of tableware and kitchenware of plastics imported in 2018. It also surpassed all the other subsequent imports of the targeted SUPs during the five (5) year period assessed with approximately 3280 metric tons entering the country. However, a significant drop in imported volumes of more than 90% of other plastics was noted in 2019 which coincides with COVID-19 pandemic. The decline in imports applies for all the classes of products with a gradual increase noted in the latter years though the numbers do not return to the peaks observed in 2018.

The pandemic and subsequent lockdown of borders had a strong impact on the tourism industry thus the sharp decline in SUPs as well as the shipping industry with delays affected imports of goods. Moreover, the start of 2019 was when the plastic shopping bag and plastic straw ban was implemented in Samoa which can account for the rapid decline in the "polymers of ethylene" class compared to 2018.

The year 2022 shows an even distribution of targeted products imported however the amounts remain well below the years prior to the COVID-19 pandemic. Imports of carboys, bottles, flasks and similar articles remains constant throughout the period of interest with polymers of ethylene and other plastics demonstrating the greater fluctuations. Due to the classification at the source by Tariff Codes, plastic products of similar class are combined thus this is not an exact depiction of the targeted SUP. This is one of the limitations to be discussed in the next section.

1.3 Exports

The amounts of export are borderline negligible when compared to the import volumes of the targeted SUPs. Table 3 below presents the dataset on exported SUP weights which was then graphed in Figure 3 to identify potential patterns and trends.

Table 3 Total weight (metric tons) of targeted SUPs exported from 2018-2022 by HS Code classification. Data sourced from SBS

Year	Weight (metric tons)			
	Of polymers of ethylene	Of other plastics	Tableware & kitchenware of plastics	Carboys, bottles, flasks and similar articles
2018	0.21	0.0012	6.60	0.065
2019	0	25.00	0.33	0.045
2020	0	0.12	0.28	0.005
2021	0	0.05	3.69	10
2022	0.23	0.05	0.37	0.06

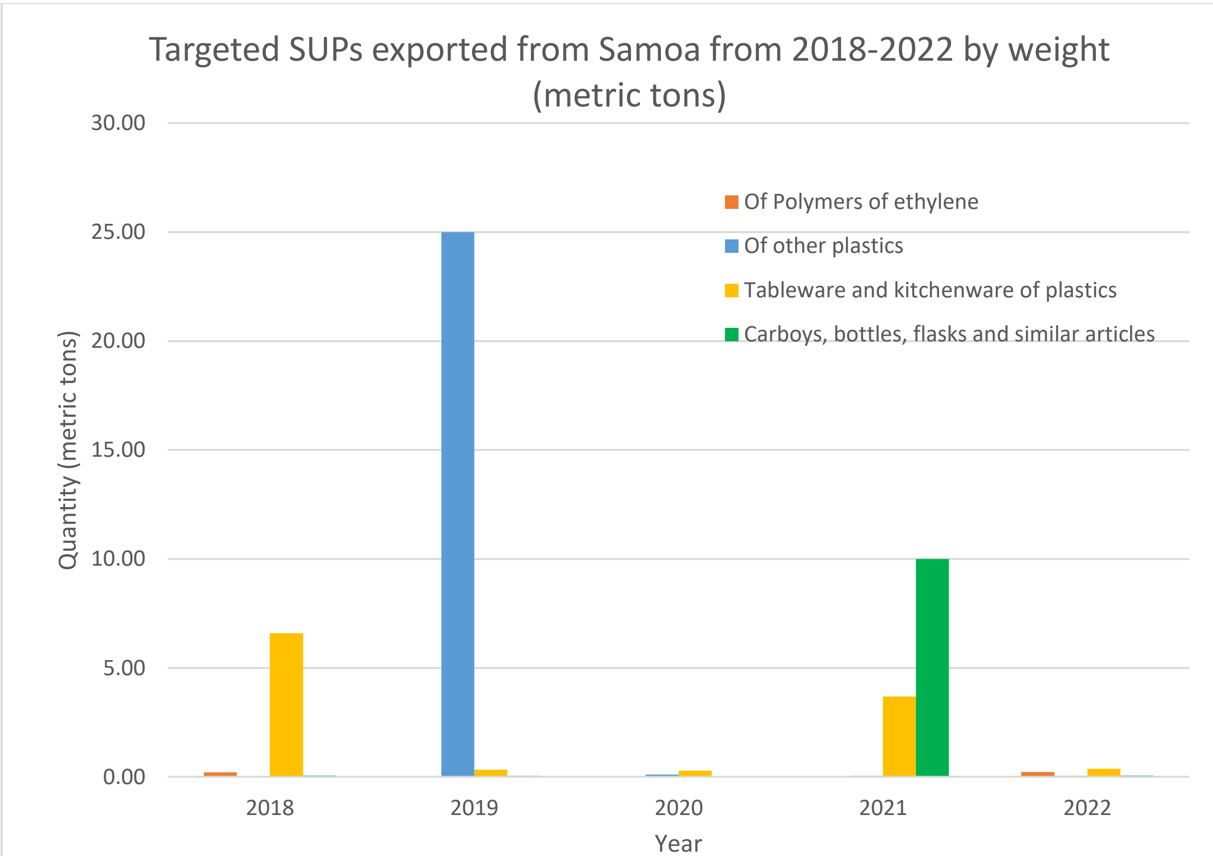


Figure 3 Targeted SUP's exported into Samoa from 2018-2022 by weight. Data sourced from SBS

With the maximum being 25 metric tons of "other plastics" exported in 2019, the majority of values remain well below 1 metric ton. The second peak observed shows 10 metric tons of carboys, bottles, flasks and similar articles exported in 2021 when the pandemic lockdown was easing up. Tableware and kitchenware of plastics are also noted to have been exported in 2018 and 2021 at a more noticeable amount while other classes of SUPs exported from Samoa were marginal. As such, the amount of SUP that remains in the country is significant and contributes to the plastic waste problem. In other words, the reliance on disposable SUP imported products remains high thus the potential level of substitution with PHAs is also great.

1.4 Private Sector Perceptions on Plastic Use

The survey questions were posed to address objectives on application, technical processing, exports, and end of life scenario as well as perception on plastic use in Samoa. Due to the small number of major companies involved in the movement of plastics, the sample pool was also limited and not randomized. The participant companies are distributors of disposable SUP with a small portion involved in packaging local products and water for local sales and exports. The majority of the participants also exhibited a lack of awareness of recycling facilities like SWRMA that take in plastic bottles, aluminum cans and glass bottles with only 1 participant acknowledging their damaged plastic bottles are diverted to this facility. All participants state their damaged plastic products end up in the landfill as the lack of recycling facilities in Samoa provides limited options.

The overall perception on plastic use and reliance in Samoa was that it was a “necessary evil” as the cost of manufacturing plastic products vs biodegradable alternatives was too competitive. As such, they do not foresee the plastic problem reducing anytime in the future at this rate. However, many were receptive of the idea of a locally produced bioplastic alternative and are supportive of the initiative should it proceed. In the meantime, the participants suggest more awareness initiatives, at a young age, of the lifecycle of plastic products as well as their impact on the environment. Wider promotion on the location of recycling bins from SWRMA would also be welcomed for improved waste management by the public.

1.5 Limitations

1.5.1 Limited access to information directly

This study possesses potential limitations, one of which pertains to the direct accessibility of available data. The channels utilized for data access necessitated formal requests directed towards upper management, outlining the study's purpose. Additional inconveniences encountered included the turnaround time for requested information. While not consistently observed, there were instances where the information provided was incomplete. For instance, there has been intermittent absence of data pertaining to certain categories of plastics for a period of three years or a few months which caused slight delays.

Furthermore, the identification of specific plastic products has proven to be challenging due to the sorting of import data according to HS Code as other products that fall under the same category are bulk listed in the one HS Code. As such, the data received is not the true or absolute representation of the volume of targeted SUPs entering the country but more of a class of plastic products lumped under one category. This limited our ability to break it down to specific items thus the class is a more accurate description of the volumes reported. In short, direct access to the raw data was a limitation that cost time.

1.5.2 Limited flexibility

The structured nature of our quantitative approach allows for consistent data collection and analysis, but also limits our flexibility to adapt and modify the research process in response to emerging insights and ideas. For instance, while conducting the survey on the application and movement of plastics in Samoa, it occurred halfway through the interview schedule that questions on their motivation to recycle as well as their level of awareness of the effect plastics have on the environment, should have been included. These queries would contribute to gauging the commitment, support and market for bio-plastics in Samoa. With the study already underway, it wasn't easy to make changes part-way through.

1.5.3 Generalizability

Our study consists of a component that depends on the use of questionnaires for data collection. Although we have put significant effort into designing and testing the instrument, it's possible that inaccuracies or misunderstandings could potentially affect the validity of the data collected. Due to the small pool of large corporations on island, the sample size was not randomized. While this has the benefit of getting deep, contextualized and interesting insights, it also means that findings that are representative of the small sample group may not be generalizable to the larger population.

In summary, this activity was able to highlight Samoa's reliance on importation of plastics, where close to 1,500 tons of different plastics were recorded to have been imported in the year 2022. Evidently this amount of plastics being brought into the country is alarming as it poses a threat to Samoa's environment. However, it was also noted from the data collected that different industries require different levels of strength, flexibility, and durability from their materials. For instance, packaging materials need to be strong enough to withstand transportation and handling, while medical implants require flexibility and biocompatibility. By tailoring the synthesis process or blending different types of PHAs, it is possible to achieve the desired mechanical properties that imitate the properties of traditionally used plastics. Whilst also promoting sustainability and relieving pressure off Samoa's landfill with the biodegradability of PHA.

2. Resource Availability and Technological Options

This section provides information on various commercially available agricultural wastes for PHA production and their current applications in multiple sectors. Additionally, identifying the most viable agricultural waste for the production of PHA and furthermore, provides an insight into the potential technologies most appropriate for this biopolymer in environmental, industrial, and biomedical applications.

Thus this section explores the agricultural wastes otherwise known as green waste, present in Samoa and investigate their potential to be a feedstock option for local PHA production. As well as identifying the technology that is compatible with the resources available in Samoa and is energy efficient to coincide with Samoa's energy capacity. To aid this research, this report will focus on achieving the following:

- Identify potential waste streams for a sustainable feedstock for PHA production in Samoa
- Assess biomass available, and quantify if it has the capacity to meet the sought after input and output volumes needed for production.
- Analyze waste streams to identify whether it has the suitable properties required for PHA production.
- Recommend potential technology to conduct a small scale pilot study locally that is also energy efficient.

2.1 Data Collection and Processing

Due to the limited or lack thereof green waste generation data in Samoa, surveys were conducted to create a baseline to create an analysis on potential waste streams in Samoa for PHA production. This entailed conducting a survey and site visits with the aim of assessing biomass availability to determine whether they are suitable for PHA production as suggested by the numerous research articles and preliminary study trials. The target population that was considered was those that would have the capacity to produce sufficient amounts of waste, which included crop exporters, commercial farmers, hotels, restaurants and organic by-product factories, such as taro chip producers, oil manufacturers etc. As large scale producers were the focus, commercial farmers were selected based on the sizes of their plantations, ideally larger than 5 acres. As for the selection of hotels and restaurants, only the hotspots in Samoa for tourists and consumers were contacted as they regularly accommodate large quantities daily.

MAF farmer contacts were utilized as MAF are heavily affiliated with commercial farmers and exporters in Samoa. These contacts were some of the main targets of our data collected through surveys. In the case of hotels, restaurants and factories, they were contacted prior to visits where they were happy to cooperate with the survey. The data collected from the interviews were then analyzed to determine which avenue or industry would most likely be the best waste stream option and to better inform recommendations for future progression of PHA production in Samoa.

In addition, a literature review focusing on successful trials of PHA production, successful feedstock options and the potential technology that can be adopted by Samoa for a small scale production was conducted. This was done to better understand the local resource availability and how this can be utilized and consider the different production options that will be feasible.

2.2 Feedstock Options and Available Technology

Organic waste streams for PHA production would need to possess certain characteristics and make it suitable for microbial fermentation or enzymatic conversion into PHA. Examples provided in studies overseas include: food waste from households, restaurants, and food processing industries; agricultural residues such as crop residues and fruit pomace; wastewater treatment plant biosolids; and industrial waste streams rich in organic matter, such as brewery waste.

2.2.1 Elements in the process of PHA production

PHA are a group of biopolyesters that have gained an exponential increase in studies and pilot trials for their potential application as thermoplastics due to their biodegradability. Over the years there have been many attempts; however, there have not been many successes. A contributing factor for this is due to their comparative higher production cost to petroleum-based plastics. However in some successful trials it is noted that the successful production of PHA is heavily dependent on the selection of a carbon source. The purpose of this is to ensure the optimal performance of the bacterial fermentation process along with the desirable nitrogen content. Carbon sources are required for the bacteria growth which is a fundamental aspect of PHA production, as this is the bacteria that will break down the used feedstock source. Traditionally carbon sources used is glucose, although it is suggested that using a renewable carbon source such as agricultural by-products and wastes as an alternative substrate can potentially reduce production costs by 40-50%. According to studies, bacterial species produce PHA during the early stages of growth when there is an abundance of nutrients. PHA accumulation however, is best under nutrient stressed conditions when nitrogen, phosphorus and other elements concentrations are minimized. Therefore different concentration ratios will influence the levels produced as well as the time taken for accumulation (Mayur G. Naitam, 2022).

As previously mentioned carbon sources play a crucial role in the success of PHA production, simple sugars are known to be the easiest and best choice of carbon sugars for the most abundant PHA producing bacteria. For that reason, choosing the right feedstock is of utmost importance in PHA production.

2.2.2 PHA production technology and equipment required for a pilot study

Literature reviews show that there are more than 150 different types of PHAs, (Ester Prados, 2016) however the most common ones from a number of studies are:

1. 3-hydroxybutyrate (3HB)
2. 4-hydroxybutyrate (4HB)
3. 3-hydroxyvalerate (3HV)
4. Poly (3HB-co-3HV)
5. Poly (3HB-co-4HB)
6. Poly (3HB-co-3HV-co-4HB)

These types can be mixed in different combinations to provide characteristics that are similar in properties to traditional plastics but are biodegradable in a few days or years in a natural environment.

Despite the variation of PHAs production in large industry scales, the basic principles are similar. PHA production needs a carbon feedstock (such as agriculture waste from post harvesting processes), microorganisms of different kinds (bacteria), and fermentation process for PHA accumulation and recovery and extraction process. Once the PHAs are extracted and recovered from the bacteria. It is washed and dried and transformed into PHA monomers or polymers granules, which are then stored and packaged in large amounts. These PHA polymers can be used in conventional processing equipment such as thermoplastic molding machines for different applications.

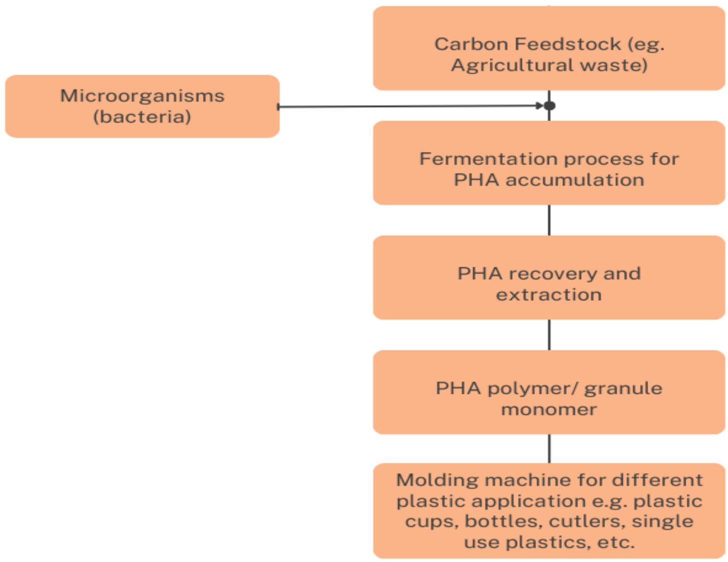


Figure 4 General PHA production flow chart.

Carbon sources are available in the form of carbohydrates, starch, oil/glycerol and sugar for microorganisms for PHAs production. However, the selection of carbon feedstock is also based on the kind of bacteria needed for the PHA production method. Literature reviews show that there are many types of bacteria that can be used for PHA productions. Some of the PHA bacteria listed by (Prados and Sergi, 2016) article is cited below.

Bacteria	PHA composition	Reference
Bacillus cereus	PHB	Ali & Jamil [29]
Bacillus megaterium	PHB	Gouda *et al.* [30]
Bacillus megaterium R11	PHB	Zhang *et al.* [31]
Bacillus megaterium strain JK4h	PHB	Dhangdhariya *et al.* [32]
Bacillus mycoides RLJ B-017	PHB	Borah *et al.* [33]
Comamonas testosteroni	PHB	Thakor *et al.* [34]
Cupriavidus necator H16	PHB	Batcha *et al.* [35]
Cupriavidus necator H16	PHB	Obruca *et al.* [36]
Haloferax mediterranei	PHB	Huang *et al.* [37]
Ralstonia eutropha H16	PHB	Kahar *et al.* [38]
Recombinant *Escherichia coli* arcA	PHB	Nikel *et al.* [39]
*Recombinant *Aeromonas hydrophila* 4AK4	P(3HB-co-3HHx)	Tian *et al.* [40]
*Recombinant *Ralstonia eutropha* H16 strain	P(3HB-co-3HHx)	Kahar *et al.* [38]
*Recombinant *E. coli* DH5α	P(3HB-co-3HHx-co-3HO-co-3HD)	Li *et al.* [41]
Bacillus sp.	P(3HB-co-3HV)	Shamala *et al.* [42]
Bacillus sp. 256	P(3HB-co-3HV)	Kumar *et al.* [43]
Brevibacillus invocatus MTCC 9039	P(3HB-co-3HV)	Sankhla *et al.* [44]
Cupriavidus necator	P(3HB-co-3HV)	Garcia *et al.* [45]
Halomonas campisalis	P(3HB-co-3HV)	Kulkarni *et al.* [46]
Methylobacterium sp. GW2	P(3HB-co-3HV)	Yezza *et al.* [47]
Recombinant *E. coli* XL1	P(3HB-co-3HV)	Yang *et al.* [48]
Serratia ureilytic	P(3HB-co-3HV)	Reddy & Mohan [49]
**Pseudomonas aeruginosa* MTCC 7925	P(3HB-co-3HV-co-3HHDco-3HOD)	Singh & Mallick [14]

3HB: 3-hydroxybutyrate, 3HV: 3-hydroxyvalerate, 3HHx: 3-hydroxyhexanoate, 3HO: 3-hydroxyoctanoate, 3HD: 3-hydroxydecanoate, 3HHD: 3-hydroxyhexadecanoic acid, 3HOD: 3-hydroxyoctadecanoic acid, *SCL-MCL-PHA co-polymer producers, **SCL-LCL-PHA co-polymer producers. Modified from Kumar et al. [12].

Figure 5 The different bacterium that can be used in the carbon source fermentation process (Ester Prados, Bacterial Production of Hydroxyalkanoates (PHA), 2016)

In general there are two methods in PHA production. Firstly, is the mixed microbial culture (MMC), in which more than one microorganism is used in PHA production under a non-sterile environment. This method follows the same flow chart as in *Figure 5*.

The second method is the pure culture (PC) where only one microorganism is used for PHA production. Since, one type of bacteria is used, the effluent batch from acidogenic fermentation has to be in a sterile environment during the PHA production process, which is the reason why PC method is more expensive than MMC method.

Given below is the general flow chart of PHA production using PC method.

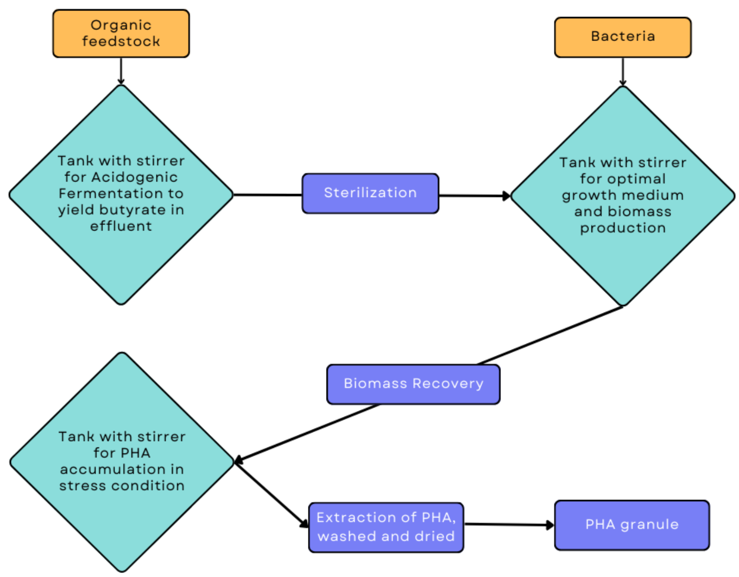


Figure 6. PC Method of PHA production general processes shown in a flow chart.

Literature review shows different manufacturers of PHA production employ different production methods and follow different processes and procedures. However, the underlying principles for PHA production among them are similar. The variation is mainly due to the design of the manufacturing plants in order to increase PHA yielding efficiency. As an example, the carbon loading rate type of substrate, temperature, pH, and others (Cabrera & Jose, 2019). Given below is one of the setups used by (ibid) to study and compare PHA production, which seems to be different from the flow charts presented in this report.

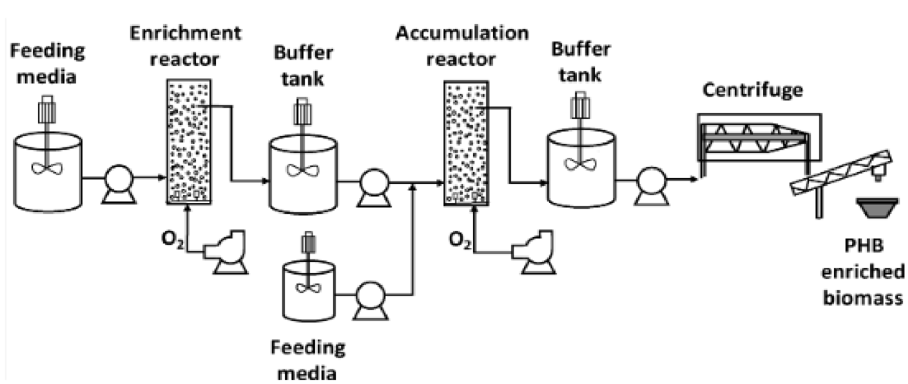


Figure 7 PHA production set-up example. (Francisco Cabrera, 2019)

Bench top scale or lab scale can be done in SROS to harvest PHA plastics. Most of the equipment is available at SROS for pioneering work. Nevertheless, the lab scale is not sufficient to produce enough PHA polymers for thermoplastic molding equipment for different applications. Hence, both lab scale and production scale are equally important in the study of PHA plastics. For instance, the selection and the nature of bacteria used, the kind of feedstock media used can be at a lab scale. However testing the physical properties of PHA plastics, such as flexibility, elasticity, electrical and material strength requires production of a significant and steady of PHA plastic.

Subsequently, if SROS is committed to study PHA plastics beginning at the laboratory scale, it is recommended a separate laboratory space is dedicated for this work. Separation of PHA processing is required as there a need to grow and handle mass bacterial growth.

2.2.3 Proven feedstock options for PHA production

In-depth research in biotechnological advancement over the years has promoted the utilization of industrial organic discard, plants, and animal wastes as potential sources for the production of PHA.

Figure below provides some valuable feedstock that are derivable from waste, specifically organic wastes that are used in the production of microbial biopolymer polyhydroxyalkanoates.

Microorganisms	Carbon source	Dry cell weight (DCW) (g/L)	PHAs yield (g/L)	PHAs accumulation (%)
Burkholderia cepacia ATCC 17,759	Glycerol	5.8	4.8	82.76
Bacillus aryabhattai	sweet sorghum juice	3.02	1.74	57.62
Brevundimonas sp. NAC1	Cardboard industry waste water	–	4.042	77.63
Enterococcus sp. NAP11	Cardboard industry waste water	–	5.236	79.27
Bacillus sp. NA10	Cardboard industry effluent	7.8	5.202	66.70
Bacillus thuringiensis IAM 12,077	Starch	3.6	2.6	72.3
Cupriavidus necator	Fructose	11.6	7.48	64.48
Pseudomonas aeruginosa	Mustard oil	–	9.01	20.1
Bacillus sp.	Sugarcane bagasse	9.0	5.0	55.55
Pseudomonas putida	Waste frying oil	4.90	2.80	57
Bacillus siamensis PD-A10	Orange peel	2.66	2.16	81.2
Bacillus subtilis JCM 1465	Onion peel	3.33	2.93	88
Staphylococcus aureus JH1	Onion peel	1.56	1.29	83
Bacillus megaterium	Molasses	–	19.52	60.02
Bacillus cereus NDRMN001	Rice bran	36.26	33.19	91.54
E. coli	Sago molasses	33.26	27.1	81.47
Paraburkholderia sp. PFN29	Glucose	5.14	5	97.3

Figure 8 Carbon source with its corresponding bacteria that produces PHA. (Shiva Aley Acharjee, 2022)

The above figure presents a compilation of agricultural and industrial waste products, food waste, fatty waste, and plant oil used as carbon sources. Each carbon source requires a specific bacterial strain which is utilized for cultivation of microbial biopolymer polyhydroxyalkanoates but also the suitable bacteria required to utilize these carbon sources for bioplastic production.

2.3 Samoa feedstock options for PHA production

Every country has some differences in climate, culture and population density. These differences result in the abundance and production of specific feedstock. Therefore, habits and traditions direct the cultivation of specific crops, and Samoa has a long history of starch and carbohydrate based crops. Majority of the population engage in agriculture, and 19% of the population utilize agriculture - post harvest as a main source of income for local markets and exports among others. Furthermore, this provides an insight on the potential agricultural waste generated locally on a daily basis. Utilizing the agricultural being generated as a potential feedstock for the production of eco-friendly biopolymers. Similar to biofuels, bioplastics can be produced from different feedstock of green waste therefore, the following provides a list of various feedstock sources available in Samoa which is recommended as a sustainable feedstock for PHA production.

1) Agro Industrial waste
2) Cooking oil waste
3) Biodegradable municipal waste and animal by-product streams

Upon research and literature review it is noted that agricultural waste, specifically green waste of post-harvest waste. To find sustainable waste streams that are able to accommodate the potential demand this process requires, industries that produce large amounts of green waste were targeted. These industries include crop exporters, commercial farmers, popular hotels and restaurants as well as factories that use natural resources that are within interest of this study.

2.3.1 Green waste generation

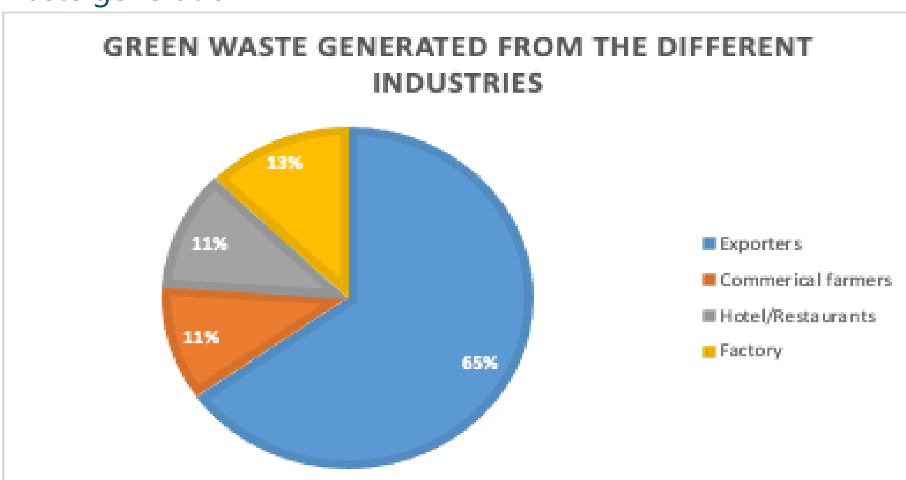


Figure 9 Green waste generation from the different industries that were interviewed.

As seen in the figure above exporters generate a marginally large amount of agricultural waste. As a result MAF were contacted regarding their exporters' details and waste data that can be seen in the tables below. This includes the average statistics on the waste generation by exporters from the MAF Atele pack house located in Nu'u from the years 2021 – June 2023.

Table 4. Atele Fresh and Frozen Taro Operation Waste Estimates 2021-2022

	No. of containers		Total weight of containers		Waste estimates (kg)	
	2021	**2022**	**2021**	**2022**	**2021**	**2022**

FRESH	85	54	902,706	522,885.2	186,000	106,000
FROZEN	41	22	282,896	72,658	26,250	6652

Table 5. Atele Frozen Crops Operation Waste estimates 2021-2022

Crop	No. of containers		Total weight of containers		Waste estimates (kg)	
	2021	**2022**	**2021**	**2022**	**2021**	**2022**
Ta'amu	41	22	36,998	12,138	3350	1750
Breadfruit			74,728	62,104	7120	5500
Yam			22,674	5,564	1925	970
Cassava			76	100	16	26

Table 6. Atele Fresh Taro Operation January - June 2023

Month	No. of Containers	Total Weight of Containers	Waste estimates (Kg)
Jan	2	17489.5	3700
Feb	5	47805	10600
March	5	39410	9850
April	2	14,765	1850
May	2	9837	1360
June	2	5943	850
TOTAL	**18**	**135,249.5**	**28,210**

Table 7. Atele Frozen Taro Operation January - June 2023

Month	No. of Containers	Total Weight of Containers	Waste estimates (Kg)
Jan	0		
Feb	0		

March	8	23306	13250
April	1	10620	2100
May	0		
June	0		
TOTAL	**9**	**33,926**	**15,350**

It can be seen that waste generation is dependent on the amount of containers that were packed and shipped for that given month. Another visible trend is that there was a higher number of containers shipped in the year 2021. Atele employees stated that a factor that contributed to this was most likely a lot more people were focusing on their plantations as a result of the COVID-19 lockdowns and job insecurity during this time.

The significant drop in container numbers this year in comparison to 2021-2022 is due to exporters developing their own container packing warehouses instead of going to Atele, which can be seen in Tables 6 and 7.

Figure 10. Taro shaving process for taro exportation in one of the exporters packing house located in Savaii.

2.3.2 Current usage of green waste

This section presents how each sector or industry that was interviewed utilizes or minimizes agricultural waste generation.

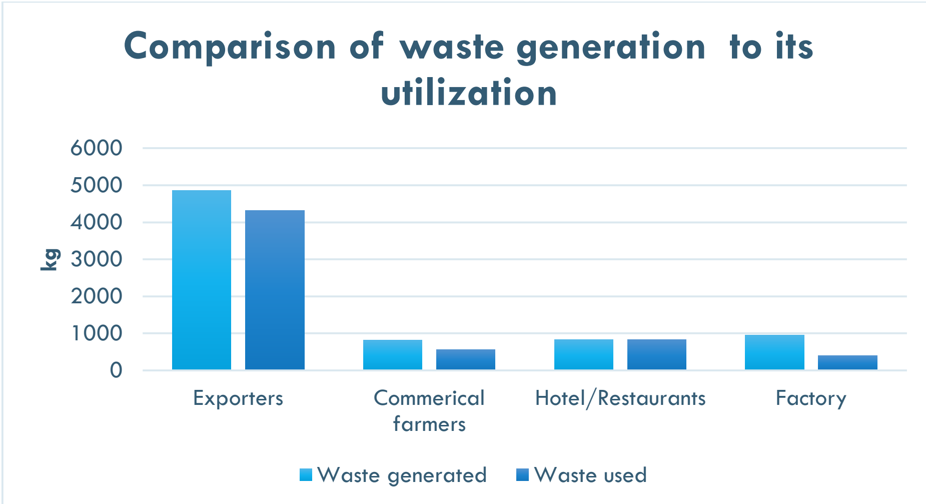


Figure 11. Bar graph comparison of the green waste produced and how much is utilized by those that were interviewed.

As seen in the graph above hotels and restaurants ensure full utilization of their green waste produced. This is a result of multiple factors as discovered through the interview process. Contributing factors to hotels and restaurants using 100% of the green waste they produce includes chefs creating dishes that minimize waste by utilizing the full crop or fruit. It was also noted that they have already established relations with farmers or pet owners who collect their waste daily as a feedstock source for their animals, which is favorable for the restaurant and hotel owners as they regularly maintain a hygienic and clean space. Some owners also have their own farms they supply the waste to.

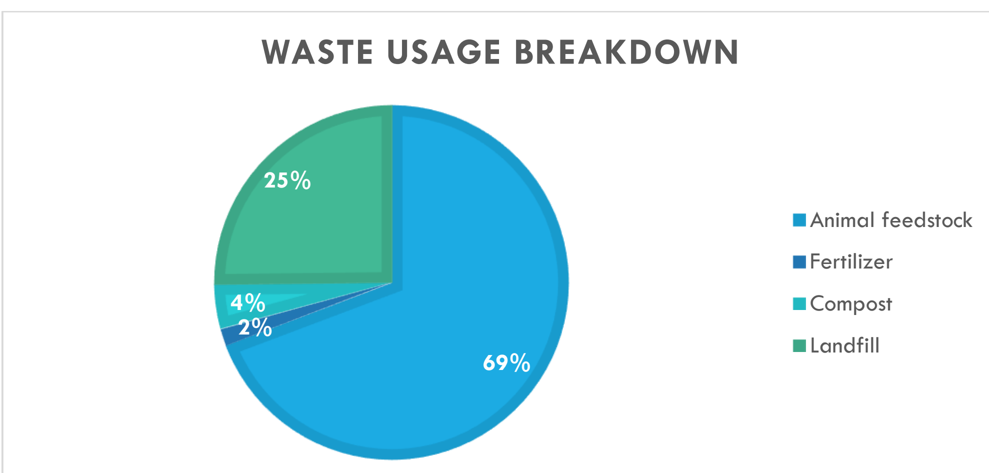


Figure 12. Pie graph illustrating the most and least used option for waste utilization as identified through the surveys conducted.

The figure above showcases the different uses of agricultural waste. The majority utilize the waste as a food supply for pigs, cows, chickens and dogs. Some of the interviewees do use the waste as compost or fertilizer mixes for their respective farms or plantations. There is a relatively large amount that still goes to the landfill and this was found to be from mostly the factories. Due to the large quantities that they produce daily, to keep their space cleared for efficient production they require clearing their waste at a timely manner otherwise the waste will rot.

2.4 Limitations

The feasibility of PHA production in Samoa is the first to ever be conducted locally, thus providing a challenge in data collection for our team. A lack of prior research on the topic was conducted in Samoa which could potentially assist with the research. Acknowledging this limitation we utilized this opportunity to develop a baseline data for any future research relative to PHA in Samoa.

In identifying our survey population, we liaise with multiple private sectors industrial business which generate a relevant amount of waste daily. However, upon request on existing data, access to these data were not permitted by the respective parties due to confidentiality according to company policies but also no proper estimation or usage of waste are recorded by businesses.

The flexibility of the targeted population heavily influenced the data collection for this research. Due to the time frame provided to conduct this activity of the feasibility study, data was collected on a tight schedule hence. Several of the contacted industrial businesses and employers did not have the availability to participate in this survey, limiting collected data to true representation of the capacity of waste generated in Samoa.

All major exporters and commercial farmers targeted are scattered throughout the islands of Upolu and Savaii, cultivating lands >5 acres which are likely located more towards rural areas of both islands. Identifying their residence location or farm location was a challenge for our team, as we dealt with inaccessible roads and unreliable verbal directions. Additionally, the targeted sample areas were so far apart that theoretically, the set out number of survey participants per day could not be reached due to the inconvenience of location and how each exporter/commercial farmer lived at opposite ends of both islands.

In summary, Samoa has a long history of engaging in agricultural activities with 19% of the population utilizing agriculture - post harvest as a main source of income for local markets and exports among others. A literature review focusing on successful trials of PHA production, successful feedstock options and the potential technology that can be adopted by Samoa for a small scale production was conducted. This was done to better understand the local resource availability and how this can be utilized and consider the different production options that will be feasible.

Samoa generates postharvest and agricultural waste on a daily basis for commercial use. As specified in findings, 65% of local green waste generated daily are by exporters during the processing and packing of local produce into containers for export, whilst other commercial farmers, hotels/restaurants and commercial factories generate a similar but smaller proportion of waste. From this collected data, green waste is currently utilized for different purposes. The majority utilize the waste as a food supply for livestock, however some of the interviewees do use the waste as compost or fertilizer mixes for their respective farms or plantations. Despite efforts of introducing various ways to recycle and reuse waste, there is still a relatively large amount that goes to the landfill and this was found mostly to be from factories. But through our survey they are made aware of a potential pathway to utilize their green waste that not only will help reduce plastic pollution for the environment but it provides locals with a cleaner and greener alternative.

3. Social, Regulatory and Environmental Factors

This section explores existing policies and regulations around the generation and disposal of organic waste, the social behaviours that influence organic waste volumes but also the use of conventional plastics, and lastly, factors in the social and environmental space that need to be considered if PHA processing is to made a reality.

Specific factors considered for this activity include:

- Identify the cultural, economic, regulatory, and environmental factors that are likely to cause disruption to the existing systems, and why and how? (including existing energy systems)
- Identify the key stakeholders involved, and assess what are the underlying cultural, social and business drivers of these stakeholders and to what extent does risk exist?
- Assess the key social, cultural, economic and educational benefits and drawbacks associated with the existing systems (cultural, economic, political, educational reasons)
- Identify potential mechanisms that would ensure the widest benefit sharing, taking into account key socio-cultural context.

3.1 Data Collection and Processing

3.1.1 Secondary sources

A national level assessment, policy documents on economic factors, waste management data and planning, energy, environment, from the Samoan government were identified and evaluated. In particular, the review focused on the regulatory drivers of a process such as PHA if it were to be undertaken. Understanding policy documents around key factors provides an insight into the context of PHA production being implemented in Samoa and also illuminate the views and approaches of the government of the day, in particular, towards key social, cultural, economic aspects of such an undertaking.

3.1.2 Semi-structured interviews

Participants for semi-structured interviews were selected from government personnel involved in the environment sector in Samoa – recruited from the Ministry of Natural Resource and Environment (MNRE) and Ministry of Women, Community and Social Development (MWCSD), as well as from locally based regional and international agencies.

3.2 Economic Factors

In a future bioeconomy, a substantial proportion of fossil-based plastics may be substituted with bioplastics, although the actual percentage is disputed. One study (Shen et al., 2009) stated that the total technical maximum substitution potential for bioplastics to replace their petrochemical counterparts was estimated to be 90% of total polymer consumption (including fibres) as of 2007. On the other hand, the United States Department of Agriculture (USDA) has estimated the upper limit for substitution to be 33%. Whatever the exact figure, substitution of this scale is likely to have a number of potential economic impacts, including impacts on the demand for oil and other fossil fuels and implications for employment levels. Potential stimuli and barriers to the growth of a bioplastics sector in Samoa also have to be considered.

Today at a global scale, the total production volume of bioplastics remains small compared with petro-plastics, which have enjoyed several decades of research and development to enhance the effectiveness and efficiency of their production. Worldwide consumption of all polymers reached about 259 million tonnes in 2012, with biopolymers representing 0.4% at 890,000 tonnes (Smithers Rapra, 2012).

From this small base, however, bioplastics production is expanding. A comprehensive market survey of bioplastics (Ceresana Research, 2009) estimated that, in the years 2000 to 2008, worldwide consumption of biodegradable plastics based on starch, sugar and cellulose – so far the three most important raw materials – increased by 600%. Moreover, according to a survey of the bioplastics industry by Shen et al. (2009), some companies reported growth rates of up to 50% per annum and production for the sector as a whole is expected to grow by an average of 19% per year between 2007 and 2020, production in 2020 being estimated at 3.45 million tonnes.

As highlighted in Activity 2 report, whether a bioplastic such as PHA is made by fermentation, or chemical polymerization, the raw materials (monomers) are generally sugars, while as the types of organic material available in Samoa is mostly from starch based crop waste. Availability of raw material for PHA processing is an important factor as it affects the cost of manufacturing the bio-plastic. In Europe for example, cost of raw material has become a particular issue for bio-plastic processing due to a large portion of cost being the cost of raw material. For Samoa, consideration must be given to not only availability, but also the movement or accessibility of that raw material for bio-plastic processing, for example, inter-island transportation etc. This will be considered and discussed in detail under Activity 4.

3.3 Environmental Factors

For Samoa's consideration, numerous other countries are now moving towards the implementation of national bio-economy strategies. For example, in February 2012, the European Commission revealed its vision for the future in the report "Innovating for Sustainable Growth: a

Bioeconomy for Europe: (European Commission, 2012a). In this strategy, significant growth is expected to arise from sustainable primary production, food processing, industrial biotechnology and bio-refineries. In turn, this is expected to lead to new bio-based industries, transform existing ones and open new markets for bio-based products.

Also in early 2012, the US government released its National Bioeconomy Blueprint, with two stated purposes: to lay out strategic objectives that will help to realize the full potential of the US bioeconomy and to highlight early achievements toward those objectives. It envisages 'a previously unimaginable future' in which two of the categories of new materials are: i) 'ready to burn' liquid fuels produced directly from CO2; and ii) biodegradable plastics made not from oil but from renewable biomass (The White House, 2012).

3.3.1 Environment Regulations

For Samoa, there is an existing legislative framework for solid waste management. It has developed several national legislations and policies that address solid waste management and control of pollution:

- Waste Management Act 2010 – solid waste collection and disposal including hazardous waste;
- National Waste Management Strategy 2019–2023 – governs solid waste management from households and businesses, including chemical and hazardous waste;
- Lands, Surveys and Environment Act 1989 – outlines provisions and penalties for littering on public and private land;
- Marine Pollution Prevention Act 2008 – covers marine pollution, including disposal or incineration of waste at sea and ballast discharge;
- Water Resources Management Act 2008 – covers pollution of water supplies, such as rivers lakes and boreholes;
- Waste (Plastic Bag) Management Regulations 2018; Waste Management (Importation of waste for electricity and energy recovery);
- Regulations 2015 – plastic materials ban for manufacturing, exportation, selling or distribution in Samoa, particularly in shopping bags, packing bags and straws.

Chapter 2 highlights some of the existing technologies for PHA/bio-plastic processing, and future developments in industrial biotechnology and biorefining will provide further opportunities to start new bio-based industries and transform existing ones. A significant increase in economic activity is expected to result, with new and increased markets for bio-based products (OECD, 2009a). However, for this to be achieved within Samoa, small steps will be of assistance to create a supportive environment as needed. Areas that would create such an environment include:

creating and maintaining markets for environmentally sustainable products, funding basic and applied research, and investing in multi-purpose infrastructure and education, for example. In addition, this would need to be combined with shorter-term policies such as fostering public dialogue and increasing support for the adoption and use of internationally accepted standards for life cycle analysis (LCA), together with a range of other incentives designed to reward environmentally sustainable technologies (OECD, 2009b).

3.3.2 Environmental Impacts

Samoa through its overarching policy for development, Pathway for the Development of Samoa 2022 – 2026, specifically mentions the need for green initiatives such as reuse, reduced waste, and eco-friendly products.

The attractiveness of bioplastics as replacements for petro-based plastics is dependent in part on their ability to meet environmental as well as economic goals. Bioplastics as well as other bio-based products, are of high societal, environmental and economic interest due to:

- Their use of renewable resources, resulting in the lower dependency of plastics on increasingly expensive fossil resources;
- Their potential ability to reduce GHG emissions throughout their lifecycle, compared with petroplastics, and the potential for more sustainable industrial production of plastics (e.g. by reducing GHG emissions);
- Their potential to offer better recovery and recycling options than petro-plastics and other materials, including often high biodegradability or compostability;
- Their scope to enhance industrial competitiveness through new innovative eco-efficient bio-based products and applications; and
- The higher job creation potential of bio-based products compared with that for biofuels

3.4 Social/Cultural Factors

Understanding the complexities of the social context of a typical village in Samoa is required for better comprehension of the review findings. Recognising the ideologies held by village communities was also crucial for reflecting on the findings, because generation of organic waste and also utilization at times, is usually at the family and village level. Here, the local governance systems and the village's dominant set of beliefs on kinship and religion will be discussed.

The dominant form of governance within village communities is based on a traditional system. During the period of colonisation in Samoa, efforts were made to adapt local traditional governance structures to a more modern structure, alongside that of the central government (Afamasaga, 2006). However, by the time of Samoa's independence in 1962, the traditional systems remained and these continue to be used. The village councils' authority and power were finally given recognition within the formal legal system in 1990 through the Village Fono Act 1990 (Agaiava, 2014; Macpherson, 1999). Thus, the majority of Samoa's people live within villages which have their own traditional authority. In the context of the modern state, the traditional governance systems are central to maintaining order and it is through these traditional governance systems that central government initiatives are implemented in the villages (So'o, 2006).

There are two types of villages: the *nu'u mavae* (traditional villages) which are the more common type, and *nu'u le mavae* (non-traditional villages) comprised mostly of free-hold land (as opposed to customary land as in traditional villages). The main difference in the two types of village is the governance structures. Non-traditional villages do not have a village constitution or village council and are usually located in close proximity to urban centres. The families live as individual households and make decisions based on the wellbeing of their own households as opposed to the wider community or village. A *nu'u mavae* has a clear governance structure with specific groups, each with a role to play in maintaining social order within the village community. Although there may be some slight differences in structure, most *nu'u mavae* will have broadly similar features and functions as outlined below.

Traditionally, the group which holds the highest authority in a *nu'u mavae* is the village council. Ultimately, the council is responsible for the village's wellbeing and makes its decisions based on the village *fa'avae* (constitution). Such constitutions are unwritten and based on customary practices and beliefs. The council is made up of the village *matai* (chiefs), and a *matai* can be either male or female, so long as they hold a chiefly title. Each family will have its own *matai(s)* to represent them in the council. The *pulenu'u* or village mayor is elected by the council to act as an intermediary between the village council and the central government. Central government relies on the local councils to implement government programmes and projects within villages, as it is the council rules that impact on local communities on a day to day basis, as opposed to central government laws.

Aside from the *matai*, there are other social groups that are essential to completing the traditional structure of the village. First, there is the *aualuma* (women's committee) whose main role is maintaining peace within the village. Other typical responsibilities of the *aualuma* include producing wealth for the family and village, usually by making Samoan artefacts, and addressing health, education and hygiene issues. The second group are comprised of the village *taulele'a* (untitled men). The main roles of the *taulele'a* are to implement and enforce the council's decisions, provide labour assistance for families within the village when in need, and provide food through farming and fishing activities. Together, these three groups form the local government body in a Samoan village. Amosa (2010) provides a clear illustration of this social structure. Christianity is the dominant faith belief in Samoa. The way of life of most Samoans is largely affected by the interlinkages between the traditional systems led by the village council, and religion (Thornton et *al*., 2010). The strong link between tradition and the church can be seen in the way that *matai* are often given high roles in the church. Thus, religion becomes entrenched in tradition, and from there, the church also has the opportunity to influence social issues within villages.

In summary, traditional practices through village councils have been crucial in the provision of peace, food, and general development of the villages. Village governance is undertaken almost independently from central government and local councils generally work to develop the social well-being of communities based on traditional practices. Macpherson (1999) emphasises the extent to which the communities in Samoa continue to live by these ideologies. "Today, 82 percent of Samoa's land remains in customary ownership…some 80 percent of the population lives in villages; and approximately 90 percent of the Samoan population claims, in the census, to live under the authority of a *matai*" (Macpherson 1999, p.89). Finally, Christianity has had a huge influence in Samoa and the church is now also an integral part of the village life.

4. Implementation Considerations

This section investigates to provide a holistic view of PHA production for Samoa and offer recommendations for realistic implementation. This report section determining the following.

- Identify and compare technology types according to feedstock availability, cost-effectiveness, environmental impact, and process productivity.
- Specify operational requirements, such as water, energy, effluent management, capital cost and steps to develop required infrastructure.
- Determine crucial design and operation factors.

4.1 Feed stock control and access

Chapter 2 found that establishing a consistent Feedstock proved to be a challenge. Of the agricultural types surveyed, exported taro had the highest amount of waste produced. However, this amount is dependent on the number of containers filled per month which can vary, on average between 2 to 5 containers each month. Looking into the usable portion, it was seen that 25% of green waste from such agricultural exporters from a fresh source, had over 0.5 tonnes of taro per month be underutilized and wasted to landfill. As such the following recommendations are made:

- The largest amount of waste, thus having feed stock potential, is fresh exported waste taro with an underutilized portion of >0.5 tonnes per month. Additional capacity would be required to support a pilot scale production.
- Samples of the feed stock must be taken to enact trials for the fermentation process and transport infrastructure must be planned for smooth transition to plant.
- Co-ordination and agreement with key agricultural stakeholders as feed stock providers.

4.2 Technology types

4.2.1 Production methods

According to Activity 2, the two mechanisms for PHA production analyzed were mixed microbial culture (MMC) and Pure culture (PC). Where, MMC utilized a range of bacteria and did not require a sterile environment while, PC is vice versa. The use of either of these methods is dependent on the type of feedstock and operational environment available. Each method is then compared in Table 8 below.

Table 8. Comparison of Pure Culture (PC) and Mixed Microbial Culture (MMC) methods (Chavez et al.,2022).

PC	MMC
• Works best with pure feedstock • Operates often in a one-stage process.	• Works well with diverse feedstock. • Operated in either a one stage or two-stage process.

● Requires a sterile environment which creates higher operational costs (High energy load). ● Higher PHA content % and PHA productivity than MMC. ● Often batch or Fed batch operation – giving variable quality rates and longer downtime for cleaning between batches than MMC. ● Lower capital costs than MMC as lower number of reactors and not as intensive pretreatment required.	● Does not require a sterile environment allowing lower operational costs (Lower energy load). ● Lower PHA content % and PHA productivity than PC. ● Often with either a SBR[1] or Fed-batch with multiple CSTR's[2] – maximizing productivity rates and lower downtime than PC. ● Higher Capital costs than PC as greater number of reactors, and intensive pretreatment required.

[1]Refers to sequential batch reactor set up, where batch reactors are set up in series.
[2]Refers to continuously stirred reactor set up.

From Table 8 above, the cheaper operating option that can utilize diverse feedstock like Agricultural feedstock available is recommended to be MMC.

4.2.3 MMC Process steps

According to Chavez et al., there are two ways MMC is typically set up; these are either a one stage or two-stage process. In the case of agricultural waste particularly, for carbohydrate rich feedstock like taro, a two-stage process is required where a Acidogenic fermentation stage takes place then is followed by a second bioreactor. This is because mixed cultures are unable to store biopolymers (PHA) from sugar-based compounds (carbohydrates) as such, the first stage of converting the feedstock to volatile fatty acids is imperative (2022). In Activity two this is also seen as, stage two (second bioreactor), is broken down further into Culture Selection (Optimal growth phase) and PHA accumulation (Famine phase). Therefore, in the case of this project, for Agricultural waste, a MMC setup with a two-stage process is required, in addition to pretreatment and PHA extraction.

4.2.4 Pretreatment methods

As the feedstock available is carbohydrate rich, it is imperative that a pretreatment stage take place. There are 6 types of pretreatment methods available these are Mechanical, Hydrothermal, Acidogenic fermentation, Akali, Oxidative and Combination (Zytner et al., 2023). Use of either of these methods is dependent on the type of feedstock, desired PHA production rates and complexity. In fact, the most common method used in industry for mixed microbial culture production is Acidogenic fermentation and is operated according to Zytner et al. (2023) as follows:

- Acidogenic fermentation is found to be effective for improving hydrolysis. This most commonly takes place by treating the feedstock in a bioreactor with a dilute acid (0.05 – 5%) at 160 -220 degrees C for a set period. Often with the Organic loading rate and pH being the controlled parameters.
- It is crucial that trials take place to determine the outcome of acidogenic treatment on the feedstock and to ensure acids are diluted. As, the use of strong acids can cause equipment corrosion and rapidly increase the accumulation of side effects that produce inhibitor compounds that will halt effective fermentation greatly.

4.2.5 PHA extraction methods

Following PHA production, PHA extraction phase must occur to provide a usable product, this is where all compounds other than PHA are removed. There are three ways PHA can be extracted these are, Chemical, Biological and Physical methods. Of these, the extraction method chosen is dependent on the desired PHA purity, PHA recovery, Cost, and environmental impact. From each of these methods, the most economical and ecofriendly methods have been compared below in Table 9.

Table 9. Comparison of PHA extraction solvents and methods (Kurian & Das, 2021).

Description	Green Solvent A (acetone, ethanol, Dimethyl carbonate)	Green Solvent B (Ethylene carbonate)	Akali Solvent A (NaOH)	Akali Solvent B (KOH)	Enzymatic digestion (Pancreatin)
Product Purity Percentage	91.2%	98%	88.6%	88%	90%
Recovery Percentage	70 to 80%	98.6%	96.8%	62.33%	80-90%
Cost effectiveness	Cheaper than most expensive method	Cheaper than most expensive option	Yes, cost-effective	Yes, cost-effective	No, will increase operational costs.
Eco-friendly	Yes	Yes	No	No	Yes

Looking at Table 9, the following rankings can be seen. For each category the top three options are ranked below to be:

- In terms of production quality - the highest PHA purity is Green Solvent B, Green Solvent A and Enzymatic digestion. While for PHA Recovery the ranking is, Green Solvent B, Akali Solvent A and Enzymatic digestion.
- Cost – although the most cost-effective options are the Akali Solvents in upfront costs additional operational costs would be involved to allow for post-treatment for environmental

discharge. This is followed by, the Green solvents however, this will largely be according to supplier availability. The most expensive option being the Enzymatic pathway as this would require strict storage and use requirements.

- Eco-friendly ranking- of the options available all the Green Solvents and the Enzymatic digestion options are eco-friendly and will be able to be discharged safely. Whereas all Akali options will require further treatment to allow for safe discharge.

Therefore, of all options discussed depending on the operation design, for an Ecofriendly and improved production quality, the Green Solvent B (Ethylene carbonate) proves to be the best option. However, if supplier costs are of greater concern Akali Solvent A (NaOH) would be recommended but will incur the hidden costs of additional treatment required for safe environmental discharge.

4.2.5 Overall potential process setup

Overall, the highly recommended configuration of the process is a MMC two stage process complete with Acidogenic Fermentation as a pretreatment method and the use of green solvent particularly Ethylene carbonate as the PHA extraction solvent. To meet these criteria, two potential setups have been identified; these can be seen below in Figure 15 and Figure 16 below. Each setup is mostly similar with the same pretreatment and PHA accumulation stage. However, differ in the method of Culture selection with two continuously stirred tank reactors (CSTR) with feast and famine conditions seen in figure 15 while, one SBR (sequential batch reactor) by dynamic feeding is used in Figure 16.

According to Albuquerque et al, both set ups are commendable however, in comparing the amount of PHA content % achieved in Figure 16 was the greatest at 74.6% with a VFA influent concentration of 45 Cmmol VFA/L. While Figure 15 observed a PHA content of 61% at VFA influent concentration range of 60 -120 Cmmol VFA/L (2010a; 2010b). And so, it can be said that Figure 16 ‘does more with less’ requiring only 75% of the lowest figure of VFA to produce a 13.6% higher PHA content product. Therefore, setup two, is recommended to be the most efficient option.

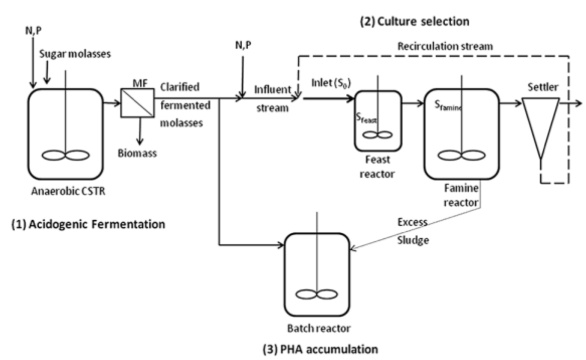


Figure 13. Pretreatment and Production stages of PHA with 2 CSTR’s (Albuquerque et al., 2010a).

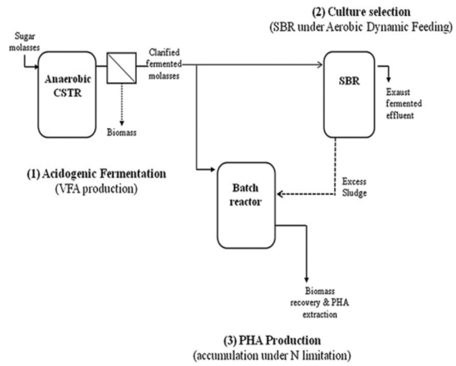


Figure 14. Pretreatment and Production stages of PHA with a SBR setup (Albuquerque et al., 2010b).

4.3 Operation requirements

4.3.1 Water & energy demand

The average water and energy demand expected from the process is dependent on the feedstock chosen and if the process utilizes residues and co-products. Looking at Life Cycle assessments (LCA) done for PHA processes, a study reviewing over 28 LCA's found that energy requirements will be higher than 50 Megajoules per kg of PHA produced. Therefore, an energy requirement of over >180 kWh would be expected for pilot scale (Baioli et al., 2019). Furthermore, a comparison of the energy and water demand for various plant capacities can be seen in table 10 below (see Appendix 1 and Appendix 2 for further breakdown).

Table 10. Comparison of Water and Energy Demand for PHA production plants.

Plant Capacity	Feedstock Capacity (kg)	Energy Demand (kWh)	Water Demand (m^3)	*Reference
Small scale (1kg PHA)	14.05 (kg COD)	2.06	0.07	Del Oso et al., 2023b).
Large scale (1000kg PHA)	79,100	4,766.9	3,603.5	(Del Oso et al., 2023a).
Estimation for 0.5 tonnes available.	500	30.13	22.78	Estimated

*See Appendix 1& Appendix 2 for further breakdown of PHA process demands.

Looking at Table 10 the difference in energy and water demand can be attributed to different plant scales as well as differences in production steps. For example, large scale operation the largest utility demand operation is the biomass selection phase. This is also seen in the large gap in demand ranges with an energy demand range of 2 – 4767 kWh and a water demand range of 0.07-3603.5 m^3. With these numbers and using the feedstock available of 0.5 tonnes, an energy and water demand estimation was made to be 30.13 kWh and 22.78 m^3. Please note that this estimated figure is solely a rough estimation and may not represent the actual application.

4.3.2 Regulatory Compliance

Environmental impact and effluent management is dependent on Environmental policies outlined in Chapter 3. Necessary licenses and permits to be obtained from regulatory authorities for operating a bioprocessing facility, handling hazardous materials, and complying with environmental regulations.

4.3.3 Production Facility

Location options of suitable plant sites are dependent on a variety of important factors - resource adjacency, energy and water infrastructure, roading access, port access etc. Based on potential technologies available, the following requirements will need to be considered:

- Space: A dedicated area with sufficient space to accommodate processing equipment, raw material storage, finished product storage, and workspace for personnel.
- Utilities: Access to electricity, water, and possibly steam for sterilization and heating processes. More detailed analysis of water and energy needs per technology type is provided in 4.3.1.
- Ventilation: Proper ventilation systems to ensure air quality and remove any potentially harmful fumes or gases generated during processing.

4.3.4 Capital Costing and Implementation

Table 11. Comparison of Capital and Production Costing for technology types (Chavez et al., 2022).

Technology Types	Culture	Feedstock	Direct Fixed Capital Cost ($USD)	Production Cost ($USD/kg)
Single Step PC	C.necator H16	Glycerol	$178,925,342	$6.72
	Recombinant E. coli	Glucose	$103,699,386	$7.87
	Thermophilic methanotrophs	Methane	$61,614,960	$7.92
Two-step MMC	Mixed microbial culture	Wastewater paper mill or food industry	-	$1.77

	Activated Sludge	Wastewater	$43,833,472.13	$4.38
	Rhodospirillum rubrum	Switchgrass biomass	$119,718,664.20	$9.35

In summary, this section which looked more in-depth into feed stock control and access, technology types with a look at the potential overall set up, and an overview of expected operation requirements based on the technologies outlined. Additionally, further discussions are needed in finalizing the engineering capability, pathways for regulatory approval, drivers for different stakeholder groups and how they might be engaged, and how development and utilization of local resources can be maximized.

4.3.4 Personnel

To operationalize a pilot PHA processing line, qualified personnel with expertise in bioprocessing, microbiology, chemistry, and engineering is required.

5. Recommendations and Way Forward

5.1 Opportunities

- Build on data inventory - Due to certain constraints, several sections that necessitate updating in the future comprise the:
- Analysis and input of missing data on import and export volumes upon receipt (updated),
- Comprehensive evaluation of the Waste Audit Report conducted by the World Bank to ascertain the quantities of plastic waste that have been documented at the landfill.
- Identify most suitable PHA material to prioritize and pilot - One aspect to consider when matching PHAs to local requirements is the mechanical properties of the polymer. Different industries require different levels of strength, flexibility, and durability from their materials. For example, packaging materials need to be strong enough to withstand transportation and handling, while medical implants require flexibility and biocompatibility. By tailoring the synthesis process or blending different types of PHAs, it is possible to achieve the desired mechanical properties.

  Another important consideration is the degradation rate of PHAs. Some applications may require a rapid degradation rate, such as single-use disposable products, while others may necessitate a slower degradation rate for long-term use items like agricultural films or mulch films. By adjusting the composition or incorporating additives into PHA formulations, it is possible to control their degradation rates.
- Establish networks with agencies experienced in PHA trials – The literature emphasizes that it is essential to match PHA production methods with local resources and infrastructure. The choice of microorganism used for synthesis therefore should be compatible with available feedstock and cultivation conditions in a particular region. In conclusion, matching Polyhydroxyalkanoates (PHAs) to local requirements involves considering factors such as mechanical properties, degradation rates, and production methods. By tailoring these aspects according to specific needs in various industries or applications, PHAs become a more viable alternative to traditional plastics in Samoa. This is difficult to pilot without observing firsthand and learning from experienced personnel.
- Build on established contacts - Continual communication and building on established partnerships with local counterparts such as SBS and MNRE are to be encouraged, as maintaining good relations with corporations allows for streamlining of requests for information.
- Growing interest in bio-economy initiatives - In the process of conducting the surveys there was a lot of interest shown by those interviewed on the topic of utilizing waste to produce another product. This added to their cooperation, and it became apparent that the concept of a green economy and clean environment for Samoa is captivating and increasingly supported by many.

5.2 Constraints

- Scarce information available on organic waste - For the future progress of PHA production in Samoa, in terms of technology, resource availability and production options potential feedstock options have been identified. However, identifying a consistent and sustainable source remains an issue. As the majority of green waste generators that were interviewed, already have uses for the waste they produce. Due to this and other mentioned constraints there may be more businesses and commercial farmers to be identified and interviewed to update the baseline of organic waste data that has been established thus far.
- No local experience in PHA technologies - The technology component for simplistic modelling of a small scale will be the priority progressing forward with this initiative. Although a preliminary literature review was undertaken through this study, an in depth research into the different methods of bacterial fermentation of specific carbon sources will need be further studied, ensuring which method is most applicable to the resources present in Samoa, as there are two main methods identified. Because this initiative is new to Samoa, establishing partnerships with overseas research agencies with experience in the space will allow for valuable exchange of technical information and experiences.

5.3 Next Steps

Upon completion of the PHA feasibility study, the following recommendations are proposed to guide the implementation of bioplastic initiatives in Samoa:

- Build on data inventory – the following analysis was not undertaken during this study due to time constraints, but building on the data that was collected will further strengthen bioplastic initiatives;

- Analysis and input of missing data on import and export volumes upon receipt (updated),

- Comprehensive evaluation of the Waste Audit Report conducted by the World Bank to ascertain the quantities of plastic waste that have been documented at the landfill.

- Identify most suitable PHA material to prioritize and pilot – As stated earlier, an important aspect to consider when matching PHAs to local requirements is the mechanical properties of the polymer. Different industries require different levels of strength, flexibility, and durability from their materials. For example, packaging materials need to be strong enough to withstand transportation and handling, while medical implants require flexibility and biocompatibility. Technical feedback from more experienced PHA researchers will provide valuable guidance for this identification process.

- Establish networks with agencies experienced in PHA trials (e.g., Scion NZ) – The literature emphasizes that it is essential to match PHA production methods with local resources and infrastructure. It is difficult to pilot PHA production without first observing the process firsthand and learning from experienced personnel. Communication has been initiated with the Microbial Biotechnology of the New Zealand Forest Research Institute Limited (Scion) who have experience on PHA technologies and have confirmed their agency will welcome a partnership and visit by Samoan researchers.
- Build on established local contacts for information sharing - Continual communication and building on established partnerships with local counterparts such as SBS and MNRE will be maintained. Good relations with local corporations allows for streamlining of requests for information.
- Engagement and Education – Having a functioning PHA processing pilot study would further promote understanding of waste management, recycling practices, and environmental benefits of bioplastics.

Implementing these recommendations will assist Samoa to harness the potential of bioplastics, fostering sustainable development, and environmental resilience.

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Appendix 1

Comparison of Energy and Water Demand for 1000kg of PHA production (Del Oso et al., 2023a)

Stages	Energy Demand (kWh)	Water Demand (m^3)	*Solvent Demand (kg)	Heat Demand (MJ)	Cooling Energy (MJ)	Steam Demand (MJ)
PHA Production						
Anaerobic fermentation (79.1-ton feed in)	53.5	268.8	2489.8	379.8	-	-
VFA separation	1212.0	-	-	-	-	-
Biomass selection	2049.0	3334.7	2742.8	831.7	-	-
PHA accumulation	1380.2	-	841.9	84.7	-	-
Downstream Phase						
Pretreatment – spray drying	50.3	-	-	1310.0	-	-
Solvent extraction	10.3	-	903.1	15.8	-	-
PHA recovery	11.6	-	2709.2	-	13,890.4	770.2
Solvent recovery	-	-	-	-	130,387.5	131,039.8
Total	4766.9	3603.5	9686.8	2622	144,277.9	131,810.0

*Solvent required for each stage in descending order are Sodium Bicarbonate, Sodium Hydroxide, Propionic acid, Dimethyl carbonate, and Ethanol.

Appendix 2

Comparison of Energy and Water Demand for 1kg Scenario 1 of PHA production (Del Oso et al., 2023b)

Stages	Energy Demand (kWh)	Water Demand (m^3)	*Solvent Demand (kg)	Heat Demand (MJ)	Cooling Energy (MJ)	Steam Demand (MJ)
PHA Production						
Anaerobic fermentation (14.05 kg COD feed in)	0.11	0.07	0.10	30.35	-	-
VFA separation	0.17	-	-	-	-	-
Biomass selection	0.36	-	0.04,0.03,0.02	1.74	-	-
PHA accumulation	0.49	-	-	0.06	-	-
PHA processing						
Downstream processing	0.93	-	$(1.20.10^{-4})$, $(7.77.10^{-5})$	-	-	4.77
Total	2.06	0.07	0.20	32.15	-	4.77

*Solvent required for each stage in descending order are Sodium Hydroxide, Ammonium chloride, Potassium phosphate, Calcium chloride, Sodium hydroxide and Sulfuric acid.