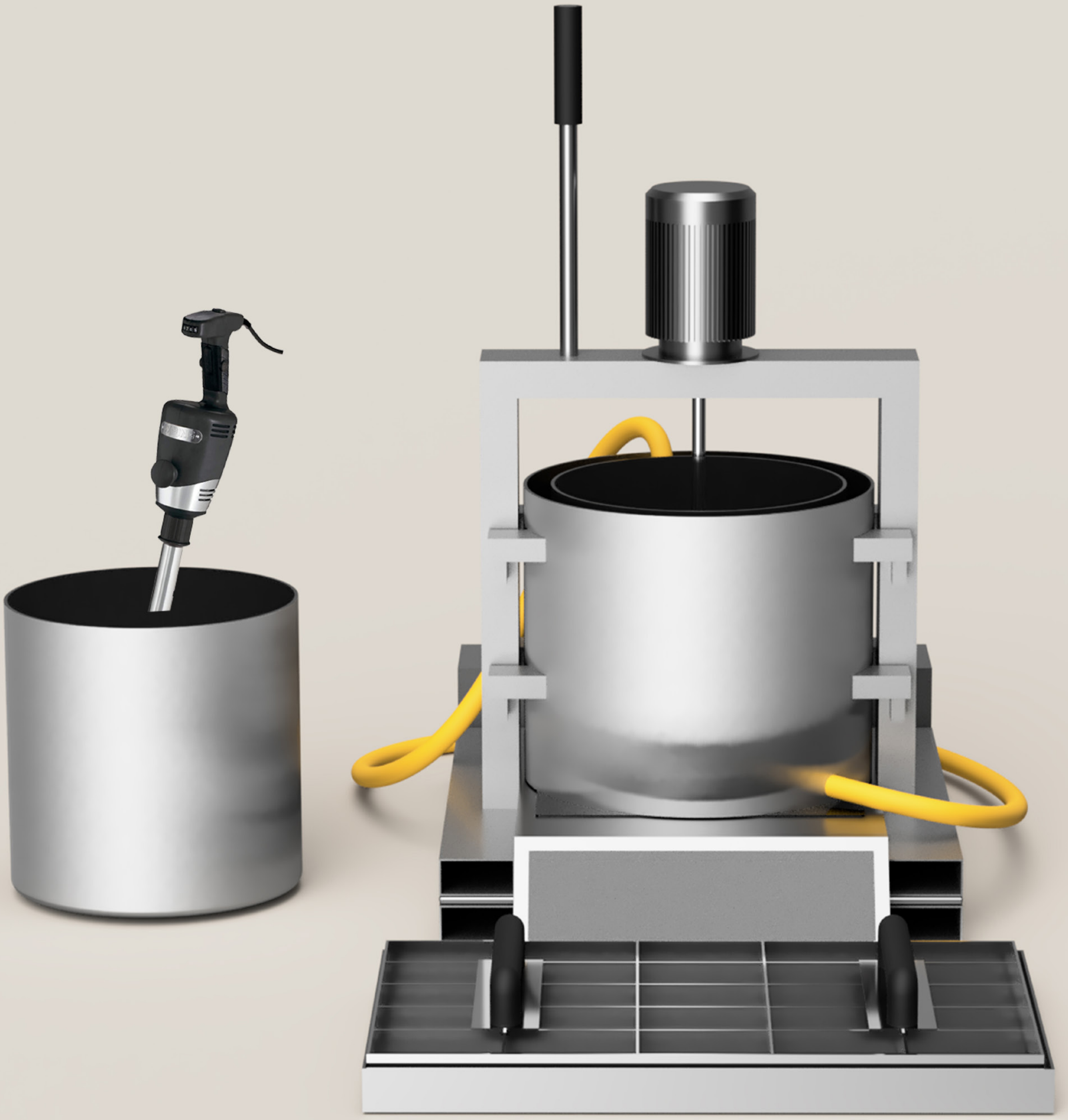
DESIGN OF A FISH REST PROCESSING SYSTEM FOR TRACEABLE AQUACULTURE AND PET FEEDS



Lucas Frantzen
21-01-2026
Integrated Product Design

Committee
Benjamin Sprecher
Joost Alferink

SUMMARY

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Introduction

At present, millions of tonnes of marine materials are processed into fishmeal and fish oil. These products are used as sources of protein and lipids in aquaculture and pet feed. The production of fishmeal and fish oil, and their subsequent processing into pet and aquaculture feed, requires thermal treatment that degrades DNA quality. As a result, it can be difficult to trace back the original species used as raw material. Several studies have shown that endangered shark species can be found in pet food. In addition, Rotterdam Zoo "Blijdorp" strongly suspects that shark species are present in their aquaculture feed, based on DNA testing. Although research is being conducted into alternative protein sources that do not rely on marine materials, it cannot yet fully be replaced. Fish rests will also remain available as long as fish is consumed. The aim of the study, therefore, is to investigate, and develop, a system to transform fish rest materials into traceable aquaculture and pet feeds.

Methods

Designing of this "Fish Rest Processing system" (FRP-system) was split in two steps. The first was at Blijdorp, where fish rest material of known origin could be used to replace dry aquaculture feeds. The aim of the second step was to adapt the FRP-system to one of producing pet feeds out of fish rest material on Bonaire, while ensuring traceability. First, system requirements were established for both Blijdorp and Bonaire to guide the design process. This was done through a combination of literature research and on-site research at Blijdorp. Based on these system requirements and laboratory experiments, a system prototype was built to produce aquaculture feeds. This was further developed into a concept design for producing pet feeds on Bonaire.

Results

At Blijdorp, a manual process was used to bind rest material with agar in order to produce fish feed. This process was translated into a mechanized process in a laboratory setting. Using this FRP-system prototype, several types of conventional aquaculture feed could be replicated. Based on the underlying processes, a concept design was developed for Bonaire that processed 10 kg of residual waste per hour into ready-to-use dog food portions. The core process for both systems consists of inductively cooking agar, followed by automatic cooling of the agar to 50 °C. This temperature was then maintained using hysteresis control. Subsequently, fish residues were mechanically mixed into the agar. The material was then poured into moulds and allowed to solidify in a refrigerator, after which it was processed into the required final size.

Conclusion

This research into traceable feed has identified key requirements that a system for aquaculture and pet food production must meet. The initial technical challenges associated with achieving the desired feed properties were addressed through the development of a laboratory prototype. This resulted in a process that can be further developed for the production of aquaculture feed. In addition, the process could be scaled up, a concept design has been developed to serve as a guideline for this.

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INTRODUCTION

INTRODUCTION

Millions of tonnes of marine species are taken from the ocean each year and turned into aquaculture and pet feeds, while nearly a quarter of all landings come from unsustainable stocks (Food and Agriculture Organization [FAO], 2024; Rishi et al., 2025). In 2022, 17 million tonnes of marine catches were processed into fishmeal and fish oil, representing 9% of total global landings.

Endangered shark species have been found in pet and aquaculture feeds. A U.S. study, investigating 87 pet foods, detected shark DNA in 21 samples. The endangered mako shark was detected most frequently, representing 71% of identified species (Cardeñosa, 2019). In Singapore, 45 pet foods were analysed, and 13% contained shark DNA, including species classified as endangered or near endangered (French & Wainwright, 2022). A study in Taiwan detected shark DNA in one of 138 canned cat foods, only, which again came from the mako shark (Wang et al., 2024). Rotterdam Zoo DNA-tested one type of dry aquaculture feed and has strong indications that shark DNA is present (S. Lopik, personal communication, October 3, 2025).

Research is being conducted to find sustainable replacements for fish oil and fishmeal, particularly for aquaculture feeds. Fishmeal and fish oil are used as lipid and protein sources in dry aquaculture and pet feeds (FAO, 2024). Alternatives include plant proteins, animal by-products, single-cell proteins, and algal proteins (Aragão et al., 2022). A 50% replacement of fishmeal with plant protein has proven successful in a carp species (Akter et al., 2024). However, beyond certain inclusion levels, all alternative protein sources negatively affect growth performance. Further research is needed to address remaining knowledge gaps and make these alternatives viable solutions (Serra et al., 2024).

Thermal processing negatively affects DNA quality in processed feeds, making it difficult to trace back the species of origin (French & Wainwright, 2022). Fishmeal and fish oil are produced by first cooking the raw materials, after which their lipid content is pressed out to obtain fish oil (Hilmarsdottir et al., 2022). During the subsequent extrusion process, the materials are again heated to create their final form: aquaculture pellets or dry pet feeds (Hardy & Brezas, 2022; Nielsen et al., 2025). DNA mini barcoding has made it possible to identify shark species in processed feeds, however, it does not always allow identification at the species level or capture the full range of species present (Cardeñosa, 2019; French & Wainwright, 2022).

Ongoing research focuses predominantly on including novel protein sources in feeds. Fish rest materials will remain available as long as fish is consumed. The overall aim of the present study, therefore, is to investigate, and develop, a system to transform fish rest materials into traceable aquaculture and pet feeds to support sustainable fisheries. Designing of the Fish Rest Processing system, which is referred to further as FRP-system, was split in two steps. The first was at the Rotterdam Zoo ‘Blijdorp’, where fish rest material of known origin could be used to replace dry aquaculture feeds. The aim of the second step was to adapt the FRP-system to one of producing pet feeds out of fish rest material on Bonaire, while ensuring traceability.

BACKGROUND

BACKGROUND

This section provides background on the Rotterdam Zoo 'Blijdorp', fishing on Bonaire, dry aquaculture feeds and fishmeal/fish oil. Background on aquaculture feeds covers the most common types and how they are produced. For fishmeal and fish oil its origin, production and usage are covered. For fishing on Bonaire professional fishing types are covered, how the fish is sold on the island and how Roffa Reefs aims to support sustainable fisheries.

Blijdorp

The Rotterdam Zoo 'Blijdorp' houses more than 200 fish species spread across several aquariums in their Oceanium. Not all fish are accessible to the public, some aquariums are behind the scenes and the fish there are kept for preservation purposes. There is also a section for quarantine. The fish in quarantine have just arrived from another location or are of poor health. In each aquarium conditions are kept as close to the natural habitat of the fish as possible. Lights are used to replicate a night and day rhythm. The quality and temperature of the water are regulated by elaborate water filtration and controlling systems. Dedicated staff is in charge of managing the water quality.

The fish are tended to 365 days a year by a team of around 10 caretakers. The caretakers are responsible for the wellbeing of the fish. An important activity is the feeding of the fish. Most fish are fed with "fresh" frozen fish. Each species gets a specific diet. These diets are prepared in the fish kitchen on a daily basis. An effort is made to replicate natural feeding behaviour by feeding the fish several times a day where possible. The caretakers are highly familiar with the fish and can accurately assess their wellbeing. Where necessary, medication is administered or diets are adjusted.

Blijdorp aims at setting up a fish recycling system to aid conservation efforts and to reduce waste. Standardized dry aquaculture feeds are fed in the Oceanium in addition to "fresh" frozen fish. The origin of the marine materials in these feeds is often unknown. The possible presence of endangered species in these feeds raises concerns. At the Oceanium waste materials are left from feeding fresh fish of known origin. Manual waste recycling is already implemented for small portions (300 g). Blijdorp seeks to explore the possibility of fully replacing currently used dry feeds of unknown origin with wet feed produced from its own waste materials.

Bonaire

Bonaire is an island in the southern Caribbean (Figure 1). It counts approximately 26.500 inhabitants (Centraal Bureau voor de Statistiek [CBS], 2025) and has a surface area of 288 km². The island belongs to the Kingdom of the Netherlands (Rijksoverheid, n.d.). The island is also surrounded by coral reefs (Williams et al., 2025).

Fishing is deeply rooted in the culture on Bonaire. Fishing is claimed to be the oldest profession in the Caribbean Netherlands (Rijksdienst Caribisch Nederland [RCN], 2023). Fishing is not only conducted professionally, but it is also a common leisure activity. An estimated 15-20% of the population engages in recreational fishing or fishing to supplement their income (Schep et al., 2012). Professional fishing on Bonaire has two main categories: big boat fishing and small boat fishing.

Figure 1. Location of the island of Bonaire.

Note. From File:Bonaire in its region.svg, by TUBS, 2011, Wikipedia Commons (https://commons.wikimedia.org/wiki/File:Bonaire_in_its_region.svg). CC BY-SA.

Big boat fishing refers to fishing with boats that are over 5 meters in length, as described by Mac Donald (2019). They often have a steering hut with a roof. These are powered by a diesel engine that has between 52 and 153 horsepower. Several trolling lines are used to catch fish. Trolling lines are dragged behind a boat, on the lines hooks are attached. The lines can be reeled in by hand or using a hydraulic winch (He et al., 2021). The big boats mainly target pelagic fish. Some commonly caught pelagic species include wahoo, barracuda, mahi-mahi (dolphinfish) and blackfin tuna (Figure 2) (Mac Donald, 2019).

Small boat fishing is conducted using fishing boats that are smaller than 5 meters, as outlined by (Mac Donald, 2019). These use an outboard motor with between 6 and 25 horsepower. Handlines are mostly used to catch fish. The boats stay closer to shore within around 400 meters. These mainly target reef species. Some of the frequently caught fish are yellow mojarra, French grunt, coney and yellowtail snapper (Figure 2).

The fish is mostly only gutted by the fishermen before selling it (World Wildlife Fund [WWF], 2020). On rare occasions the fish is filleted on demand. It is unclear whether the fish is gutted on the fishing boat or once the fish comes ashore. It is most likely that both happens. Young fishers tend to clean the fish ashore and older fishers on the boat (S. Lopik, personal communication, October 31, 2025). Most fish are delivered to the customers by the fishermen. A small amount is also sold directly on the dock or to customers that come to their home.

Most fish are sold to middlemen, then to customers of the general public and lastly to restaurants. A study by WWF (2020) investigated the selling structure of fish on Bonaire. The fishermen indicated they sold most of the catch to middlemen. There were 5 major middlemen on the Island. Currently, three major middlemen remain (S. Lopik, personal communication, October 31, 2025). The middlemen sell an equal amount to walk-in customers and restaurants. Most of the supermarkets on the island do not sell any locally sourced fish, only 37% does. Fishermen and middlemen also travel to Las Aves in Venezuela to buy fish there and bring it to Bonaire. A complete overview of the selling structure can be found in Figure 3.

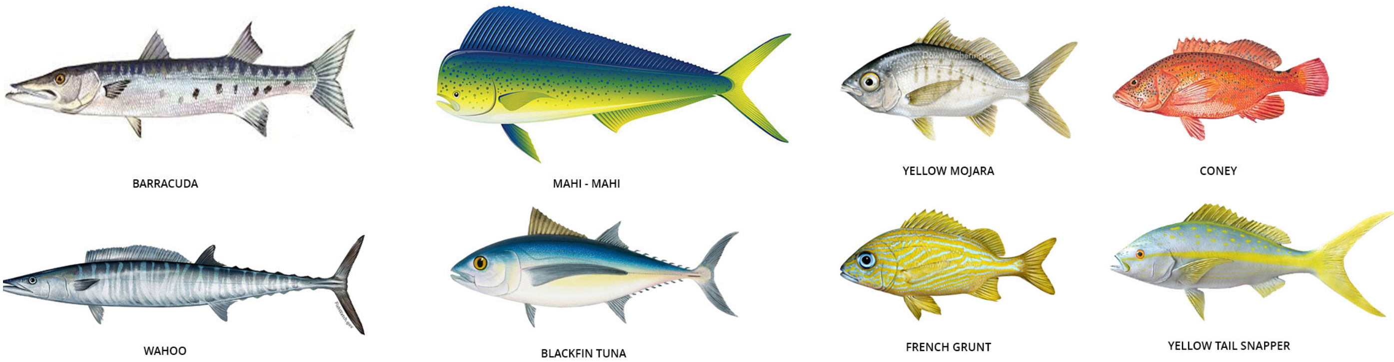


Figure 2. Commonly caught pelagic fish (left) and reef fish (right) on Bonaire.

Note. Image generated using ChatGPT.

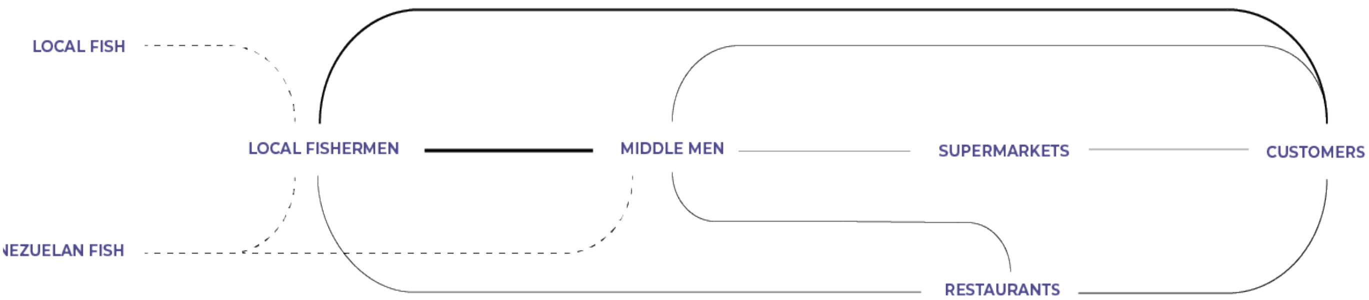


Figure 3. Overview of the fish-selling structure on Bonaire.

Coral reefs worldwide are in decline, so are the coral reefs around Bonaire. Roffa Reefs is a Rotterdam based organisation that makes an effort to counter the decline of coral reefs through breeding fish. Coral is a living species, and it relies on fish to maintain it. Because of the decline in the number of fish the corals are negatively affected. Sander van Lopik, founder of Roffa Reefs, who was working at the Oceanium as an aquarist, devised a system to breed fish. The concept was to catch eggs with fine nets, these were then hatched and re-introduced into the ecosystem. A floating hatching system (Figure 4) on solar power was brought to Bonaire and tested on the open water. Roffa Reefs wants to create a fish recycling system to create better understanding of fish feeding and to monitor fishing pressure on Bonaire. To breed fish a deep understanding of their diet is needed. Fish are commonly fed standardized dry aquaculture feeds, for which the origin of the marine ingredients is known. It has become a mission for Roffa Reefs to create aquaculture feeds of which their origin is known. On Bonaire the breeding system is ineffective if the bred fish are immediately caught by fishers. Roffa Reefs wants the fishers to fish sustainably. To do this fishing pressure should be monitored. By setting up a recycling system that converts fishing waste into a sellable product, fishers are given a financial incentive. This encourages them to bring waste materials ashore for monitoring.

Figure 4. The floating hatching system on Bonaire.

Note. From Bonaire pilot, by C. Douma, 2023, RoffaReefs (https://www.roffareefs.com/bonaire-pilot/). Copyright 2022 by Casper Douma.

Dry aquaculture feeds

Dry aquaculture feeds are defined by their low moisture content, which is lower than 10% (Jobling et al., 2001). There are two main types of dry aquaculture feeds: flake feeds and pellet feeds (Figure 5). Each of these results from a different production process. Pellet feeds are created through extrusion and flake feeds on a heated roller drum.

Most pellet feed is produced through a sequence of grinding, mixing, extruding, drying, and top coating of raw materials, as described by Jobling et al. (2001), Cheng and Sørensen (2025), and Hardy and Brezas (2022). The ingredients of fish feeds are proteins (among which is fishmeal), basal ingredients, vitamins, minerals and some nonnutritive elements like pellets binders and pigments. In addition, medications, hormones, antimicrobial agents and antioxidants might be added.

Figure 5. The main aquaculture feed types: flakes (top) and extruded pellets (bottom).

Note. Image generated using ChatGPT.

First, all the ingredients are put into a grinder. Hammer and roller mills are used for the grinding. All the ground ingredients are then mixed to create a homogeneous blend. This can either be done using batch mixers or continuous mixers. Halfway through the mixing dry pre-mixes are added to the mix. These premixes consist of minerals, vitamins, and carotenoids that are dissolved in a diluent. In the extruder, the mixture is heated to 125 – 150 °C through steam and friction resulting from mechanical work. An auger with increasingly tight flights (Figure 6) moves the doug-like mix towards the extrusion die. Water remains in a liquid state due to the high pressure. The dough is then pressed through a die with tapered holes. Due to the sudden release of the pressure the water evaporates creating air pockets in the pellets. During this process, the pellets expand, and the starch added as a binder gelatinizes, forming a stable pellet. The material comes out of the die as long noodles that are cut to the desired size by rotating blades.

By tuning the temperature, pressure, and starch content, pellets with different buoyancies can be created.

Water is removed through evaporation by a hot air dryer. The moisture from the pellets is transferred to the surrounding air that is circulating in the dryer. The fish feeds have a higher desired lipid content than the extrusion machine can handle and still create stable and durable pellets. In a vacuum coater the air is sucked out of the air pockets in the pellets. Lipid is then sprayed onto the pellets using nozzles in the coater. When the vacuum is released the lipid content enters the air pockets (Figure 7).

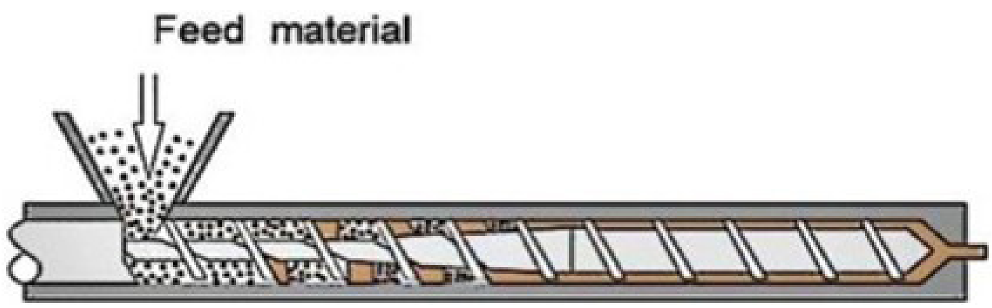


Figure 6. Cross-section of an extruder showing the auger with increasingly tight flights.

Note. From Feed manufacturing technology (p. 290), by H. Cheng and M. Sørensen, 2025, Elsevier (https://doi.org/10.1016/B978-0-443-21556-8.00008-9). Copyright 2025 by Elsevier Inc.

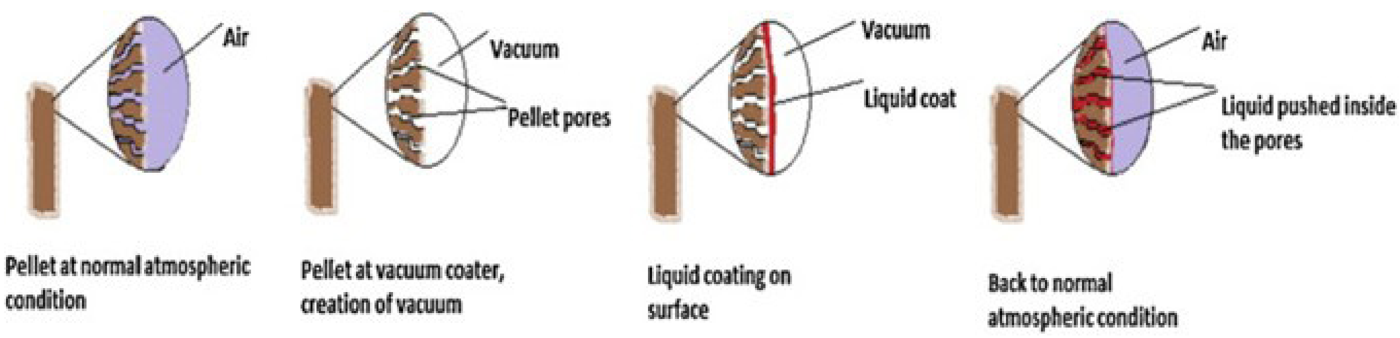


Figure 7. Illustration of lipid (liquid) entering air pockets in a pellet.

Note. From Feed manufacturing technology (p. 290), by H. Cheng and M. Sørensen, 2025, Elsevier (https://doi.org/10.1016/B978-0-443-21556-8.00008-9). Copyright 2025 by Elsevier Inc.

Flake feeds are created using a heated roller drum, chopping blade, rotating drum and screens. As described by Kumar et al. (2018) fishmeal, oils and wheat flour are first mixed in silos. The resulting thick slurry is sprayed on a heated roller drum. The material leaves this drum as a sheet, as illustrated in Figure 8. This sheet is chopped into big chunks using a blade. The big chunks are placed into a tumbler for several minutes to break them into smaller pieces. A series of screens is then used to sort the flakes by size.

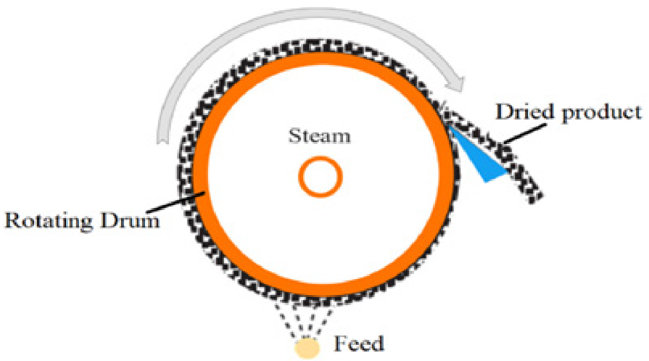


Figure 8. Schematic illustration of slurry applied to a rotating drum and discharged as a dried product.

Note. From Drying Technology in Food Processing (p. 48), by N. Malekjani , F.P. Talemy, R. Zolqadri and S.M. Jafari, 2023, Elsevier (https://doi.org/10.1016/B978-0-12-819895-7.00014-6). Copyright 2023 by Elsevier Inc.

Fishmeal and fish oil

Fishmeal and fish oil are created from whole fish or fish by products, as shown in Figure 9. Global fish oil production consisted of 46% whole fish, 22% wild capture byproducts, and 31% aquaculture byproducts. For fishmeal this was 66%, 28% and 7%, respectively (Glencross, 2025).

When sourced from whole fish, fishmeal and fish oil are mostly produced from small pelagic species (Majluf et al., 2024; Shea et al., 2025). These fish have a high oil content and often live in large shoals, making it easy to catch them in large quantities (Stephenson & Smedbol, 2001). They are the prey for larger fish species and are important to transfer energy from the plankton they eat to larger species (Alder et al., 2008). Peru makes a big contribution in the sourcing of small pelagic fish with the Peruvian anchoveta. They provided 18% of the fishmeal raw material and 11% of the fish oil material between 2013 and 2023 (The Marine Ingredients Organisation [IFFO], n.d.).

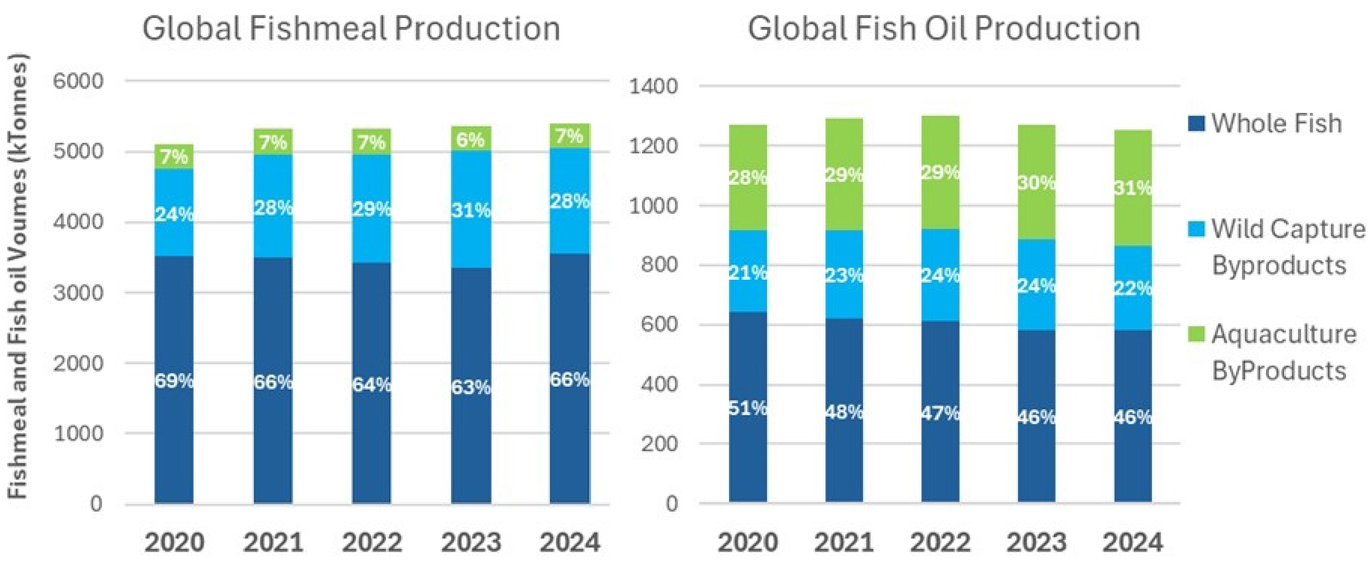


Figure 9. Global fishmeal and fish oil production by raw material input origin from 2020 to 2024.

Note. From “The Modern Face of Marine Ingredient Production,” by B.D. Glencross, 2025, Aquafeed: Advances in Processing & Formulation, 17(3), p. 47 (https://magazine.aquafeed.com/books/wolv/#p=46). Copyright 1998-2055 by Aquafeed Media, S.L.U.

By-products are materials that remain after the production of the main product in the marine industry. These include heads, frames, trimmings, viscera, and skin (Figure 10), which are used to produce fishmeal and fish oil (Stevens et al., 2018). By-products can also include by-catch, discards, weigh-backs, and diseased or dead animals (Love et al., 2024). When by-products are used, a wider range of fish types contributes to the raw material input, compared to the use of whole fish, which is largely dominated by small pelagic species (Figure 11) (Shea et al., 2025).

Fishmeal and fish oil are closely related, they are acquired in the same production process. In broad terms, the raw fish material is first pre-heated after which it is cooked. After the cooking, the liquid, mainly oil and water, are extracted through draining and pressing. The solid or cake that remains is dried using steam and air driers and forms the fishmeal. The separated liquid goes through various production steps including, decanting, centrifuging and evaporating. A part is added back as fishmeal, the rest becomes fish oil (Hilmarsdottir et al., 2021). A detailed overview of the production process is depicted in Figure 12.

Fishmeal is used in aquaculture for its favourable nutrient composition. Fishmeal

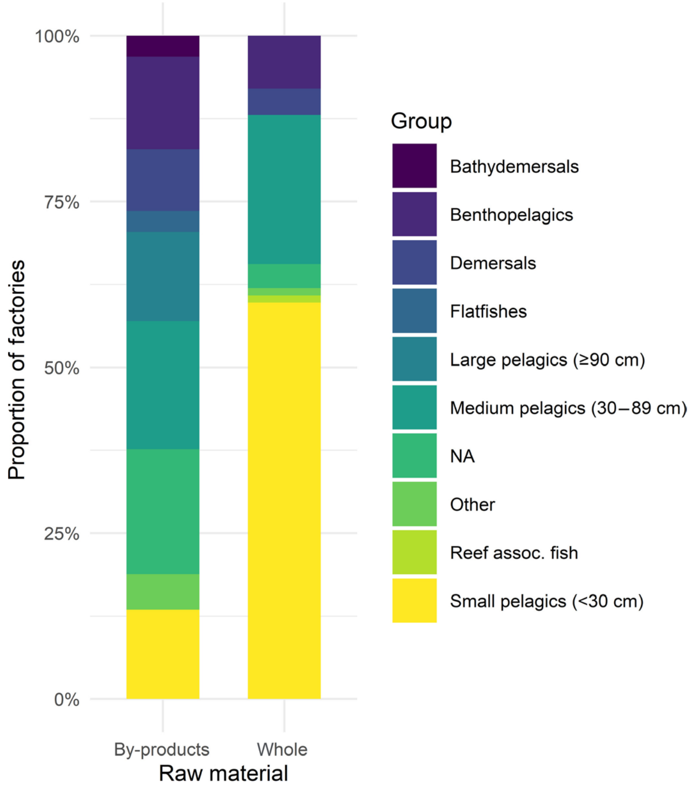


Figure 11. Relative contribution of fish groups to the raw material inputs of processing factories.

Note. From "Spatial distribution of fishmeal and fish oil factories around the globe," by L.A. Shea, C.C.C. Wabnitz, W.W.L. Cheung, D. Pauly and U.R. Sumaila, 2025, Science Advances, 11(17), p. 5 (https://doi.org/10.1126/sciadv.adr6921). CC BY-NC.

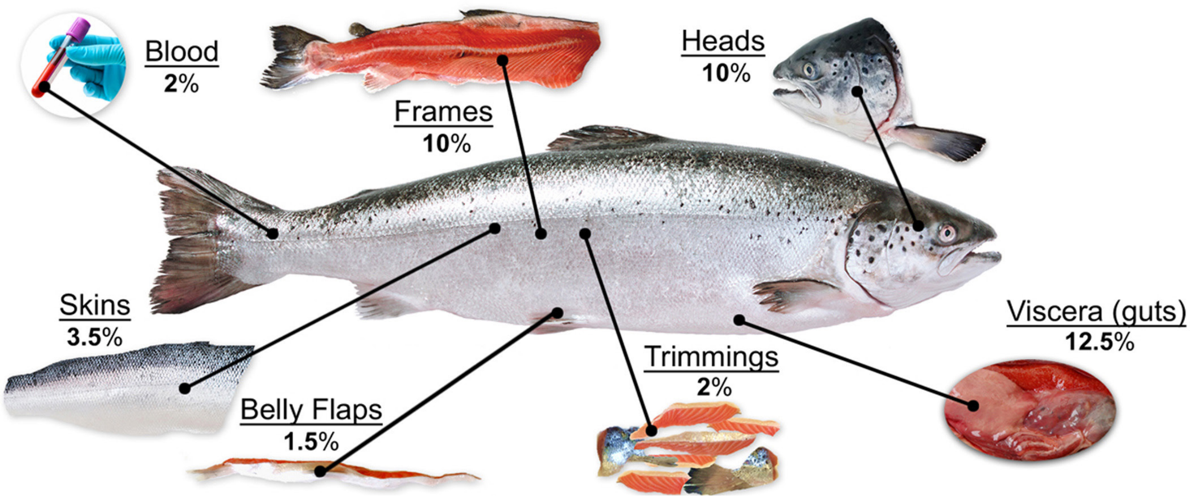


Figure 10. Graphical representation of fish by-products.

Note. From "The rise of aquaculture by-products: Increasing food production, value, and sustainability through strategic utilisation," by J.R. Stevens, R.W. Newtona, M. Tlusty and D.C. Little, 2018, Marine Policy, 90, p. 116 (https://doi.org/10.1016/j.marpol.2017.12.027). Copyright 2018 by Elsevier Ltd.

has a high protein content and the essential amino acids that make up the protein have a favourable composition (Glencross et al., 2024; Khalili Tilami & Sampels, 2018). Fish are also very willing to ingest the fishmeal because of its high palatability (Glencross, 2020).
The absence of antinutritional factors is also beneficial (Ramireddy & Radhakrishnan, 2021). Fish oil is commonly added to

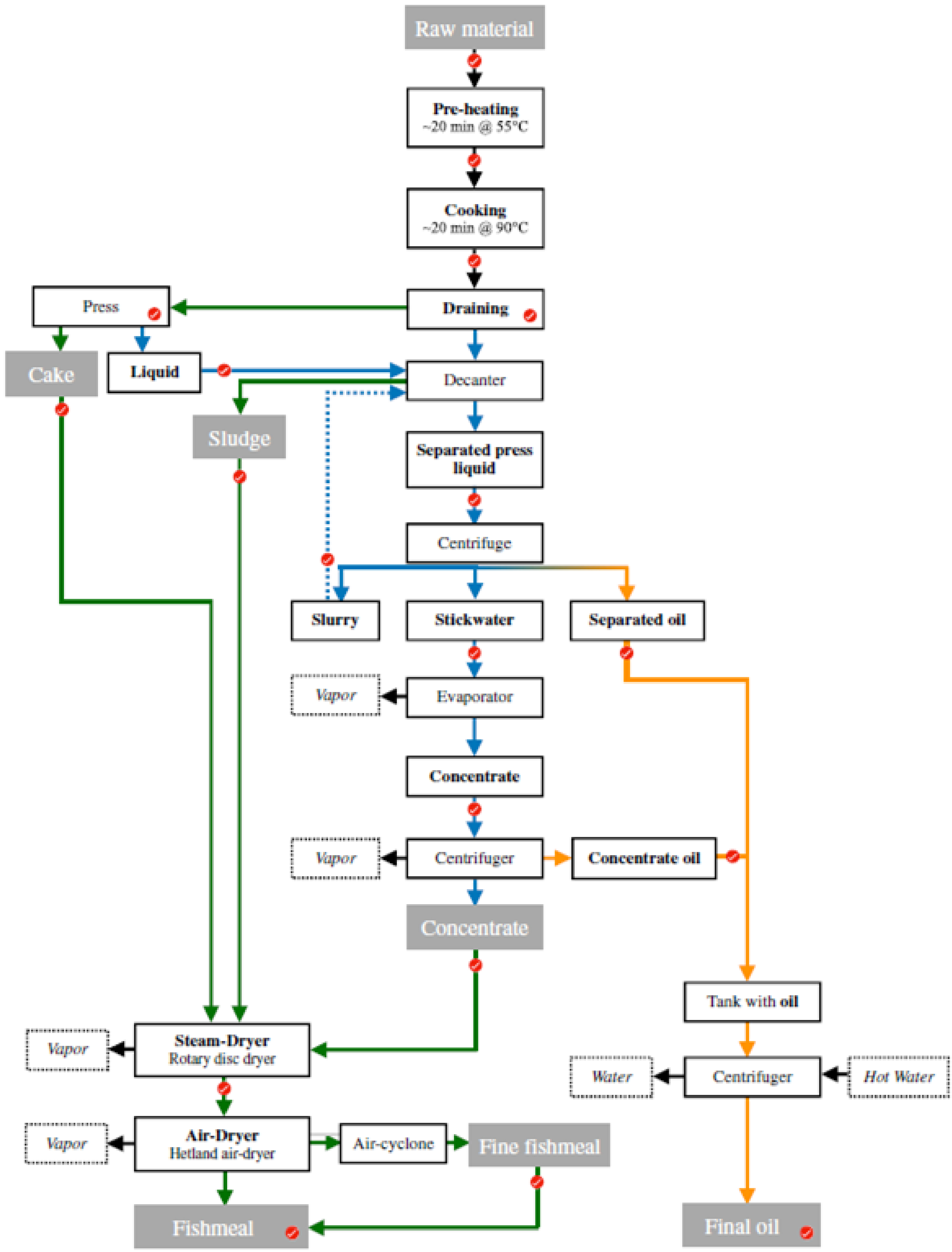


Figure 12. Process diagram illustrating the complete production process for fishmeal and fish oil.

Note. From "Efficiency of fishmeal and fish oil processing of different pelagic fish species: Identification of processing steps for potential optimization toward protein production for human consumption", by G.S. Hilmarsdottir, Ó. Ogmundarson, S. Arason and M. Gudjónsdóttir, 2021, Journal of Food Processing and Preservation, 45(4), p. 3 (https://doi.org/10.1111/jfpp.15294). Copyright 2021 by Wiley Periodicals LLC.

METHODS

METHODS

The study started with an inventory of the fish waste streams and the current, or potential, use of these for aquaculture feeds and pet feeds, respectively. The inventory was conducted separately for Blijdorp and Bonaire. The inventory was used to define the requirements to design the FRP-system. Subsequently, the designing of the FRP-system started, by testing potential components of the intended FRP-system in a laboratory setting at Blijdorp. Validated components were then integrated into a prototype of an FRP-system. Based on the prototype, a concept design for an FRP-system on Bonaire was created.

Inventory and requirements

Blijdorp

Feed usage and waste materials

At Blijdorp, the use of dry aquaculture feeds was investigated. This was followed by the identification and quantification of waste streams. A small part of this waste was recycled into fish feed. This process was also studied.

The use and quantity of dry feeds at Blijdorp were investigated and determined through a combination of observation and measurement. Dry feed was administered by caretakers, each of whom had their own preference regarding the methodology and quantity of feeding (S. Lopik, personal communication, September 29, 2025). Three caretakers were randomly selected to be observed. Each caretaker was observed while conducting a morning feeding routine, as dry feed was administered only during morning feedings. Each caretaker was asked to perform their tasks as they normally would and to express their thinking aloud. Notes were taken on paper, and photographs were taken where necessary. From these observations, the types of dry feed used were identified. The size of the feed was then determined using callipers. The quantity of dry feed used was determined by weighing the amount of feed observed to be administered during the routines. Records of the observations can be found in Appendix A. Consent to use the interview data anonymously was granted by Sander van Lopik, in his capacity as a representative of Blijdorp for this project.

Waste streams at Blijdorp were identified through observational research. To cover the complete material flow, meal preparation in the fish kitchen and shark feeding were observed. The caretakers performing the tasks were selected based on their availability. Caretakers were asked to express their thinking aloud while performing their tasks. From these observations, a graphical overview of the material flow was created. Notes were taken on paper, and photographs were taken where necessary. Records of the observations can be found in Appendix B. Consent to use the interview data anonymously was granted by Sander van Lopik.

Fish waste originating from feeding was quantified. No records of waste materials originating from the fish kitchen were kept, so this could not be quantified. The amount of waste material from feeding could be calculated from the amount fed and the amount eaten. Records of the amount eaten were kept per species or group of species. The amount to be fed was determined on a monthly basis, historic records were kept of this. Data of the year 2024 was selected for its recency and completeness. This data was collected in a Microsoft Excel worksheet (Microsoft 365, Version 2511; Microsoft Corporation, Redmond, WA, USA) (Appendix C). Data that was illegible was not included. By subtracting the amount eaten from the amount fed, the amount of waste could be determined. This was done day by day. In this manner, weekly totals could be calculated. Weekly totals included: amount of waste per weekday, amount of waste per species per week, and the total weekly waste. Using the weekly totals, yearly totals were calculated. This included the total amount of waste over the year, the average waste amount per weekday, and the contribution of each species to the yearly total.

Using the yearly total, the amount wasted from the total fed could also be calculated. For some weeks the amount eaten was missing from the records, for these weeks the averages of the rest of the weeks were used.

Current fish waste recycling practices were studied through observational research. An experienced senior caretaker was asked to perform the waste recycling process. He was asked to carry out the tasks as he normally would and to explain his thought process aloud. The full process was then captured in a graphical representation. Notes were taken on paper, and photographs were taken where necessary. A full record of the observations can be found in Appendix D.

Economic feasibility assessment

The feasibility of waste recycling was assessed by calculating the feed yield from the waste materials and conducting a basic economic feasibility assessment.

The yield of feed was determined using the total waste from feeding and a wet-to-dry conversion ratio. This wet-to-dry conversion was needed because the dry feed had a lower moisture level than the wet feed that would be created by recycling. To fairly compare them, the wet feed must be converted to a dry equivalent. The wet-to-dry conversion was based on a laboratory analysis of previously created recycled feed at Blijdorp (Appendix E).

A basic assessment of the economic feasibility of waste recycling was then performed. Waste recycling was determined to be feasible if the cost of waste recycling was equal to the cost of buying dry feed. By assuming equal cost, it could be determined how long it could take to produce a kg of recycled feed. The kilogram price of a dry pellet feed in use at the Oceanium was calculated. Using the kilogram price and the amount of dry feed used on a daily basis, the daily cost of dry feed could be determined. The amount of dry feed used was derived from observational research described in the section Feed usage & Waste materials. Using the wet-to-dry conversion described previously, the amount of wet waste material needed per day could be determined. Machine payback costs were then estimated. A payback period of two years was used. The resulting amount was subtracted from the price per kg of dry feed. This left the amount that could be spent on labour costs. Using this amount, the average caretaker salary (including overhead) and accounting for wet-to-dry conversion, the maximum time to process one kilogram of wet feed was calculated. The salary was based on the average caretaker salary in Rotterdam derived from Nationale Vacaturebank (n.d.). The overhead was determined at 30% (De Goudse Verzekeringen, 2025).

Design requirements

Findings from the Blijdorp inventory were translated into requirements for an FRP-system to be used at Blijdorp. The first requirement concerned the processing capacity, which was based on waste generated from fish feeding, as described in the section Feed Usage & Waste Materials. To replace as much dry feed as possible, the total waste quantity available should be used. The processing capacity therefore became the amount that needed to be processed on a weekly basis to utilize the entire waste stream. Three additional requirements addressed feed size and its behaviour in water, ensuring that feed produced by the FRP-system resembled the dry feed to be replaced as closely as possible. Additionally, a requirement was defined for the maximum temperature to which fish residues could be exposed. This value was derived from the current waste recycling practices at Blijdorp. Requirements regarding the shelf life and homogeneity of the feed were also based on this. Another requirement limited the maximum time needed to produce one kilogram of feed. This threshold was based on the point at which in-house production became cost-equivalent to purchasing feed, as described in the section Economic Feasibility Assessment. The value was rounded down to account for inaccuracies in the calculation.

System output traceability, as discussed in the introduction and background, was also included as a requirement. Finally, a wish and a requirement were added regarding the nutritional value of the feed, based on the background of this study.

Bonaire

Catch quantities and waste

The total yearly fish catch on Bonaire was estimated based on literature and data obtained from a local fish monger. Using these estimates, the amount of waste material available for conversion into pet feed was determined. In addition, the nutrient composition of the waste material was compared to the recommended dietary intake for pets.

Catch quantities on Bonaire were derived from literature, and the catch quantity for 2025 was estimated using regression analysis. There was no official registration system in place on Bonaire from which to derive the catch quantity (RCN, 2023). Three sources were found from which catch quantities of certain years could be determined. A study by Schep et al. (2012) calculated the economic value of the coral reefs on Bonaire. To achieve this, the study calculated the revenue of fishermen. One of the methods employed was multiplying the amount of fish caught by the average fish price. By reverting this calculation, the catch per fisherman could be calculated. From a study of Johnson (2011), the number of fishermen on the island and the average fish price in 2011 could be derived. Multiplying the number of fishermen by their income and dividing this by the average fish sale price gave an approximation of total fish catch. An investigation by WWF (2020) examined fish supply chains in the Caribbean, including Bonaire. Part of their questionnaire was an estimation of the amount of fish sold by the fishermen. Eight fishermen out of the twelve studied were able to give a sales estimation in kilograms. Based on this, the average amount of fish sold per fisherman could be determined. The study estimated a total of 30 to 40 fishermen on the island, the average of 35 was used here. From this, the total catch quantity in that year could be determined. Lastly, a study by de Graaf et al. (2016) collected data throughout 2014 and estimated the total catch through a frame survey, boat activity survey, active days survey, and landings survey. It also presented historical data on the amount of catch in previous years.

Non-scientific news reports indicated declining catches in recent years (Bremmer, 2025; Severijnse, 2025). Based on these reports and the overall thoroughness of the study, the data of de Graaf et al. (2016) were selected as the most recent and accurate. To estimate the catches on Bonaire for the year 2025, it was assumed that catches followed the general trend of the area. Bonaire is situated in the Atlantic, western-central major fishing area 31 (Figure 13). The total catches of this sector were known up to 2023. Data from 1980 to 2023 were taken from FAO's FishStatJ database (FAO, 2024). In data before 1980, entries were largely incomplete, so they were excluded. Using IBM SPSS Statistics (Version 29; IBM Corp., Armonk, NY, USA), a regression analysis was performed; it was determined that a power model provided the best fit to the data ($R^2 = 0.79$). This model and a known data point in 2014 from the study of de Graaf et al. (2016) were then used to estimate the catches on Bonaire for 2025.

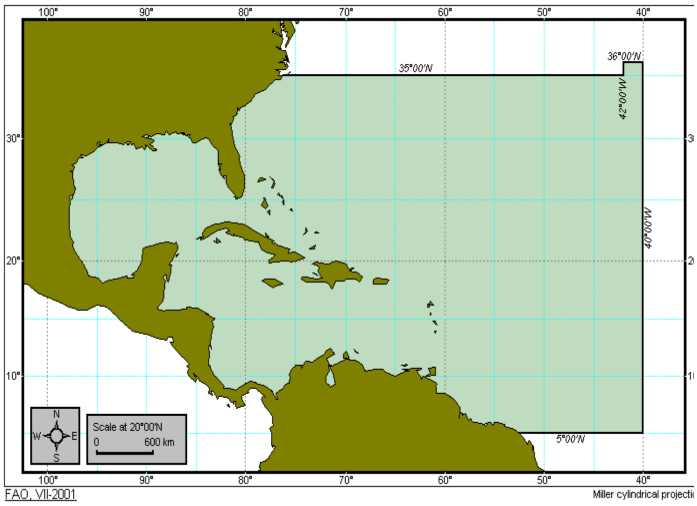


Figure 13. Map of the Atlantic, Western Central major fishing area (FAO Area 31).

Note. 2007 Capture production: by major fishing areas, 31 - Atlantic, Western Central, 2007, FAO Fisheries and Aquaculture Department (https://www.fao.org/fishery/docs/STAT/by_FishArea/Default.htm).

The catch quantity was also determined based on data provided by a local fish monger. A table containing the amount of fish provided to the monger and the amount discarded per day was provided. Based on the number of working days and the estimated number of fish mongers on the island, the total annual catch could be determined. The number of working days in 2025 was taken from RCN (2025). The same local fish monger also indicated the number of fish mongers on the island. It was assumed that every fishmonger received an equal quantity of fish.

The amount of waste material was determined based on catch quantities derived from the literature and data obtained from the local fish monger. From the background research, it was determined that the usable material for the feed was the viscera (intestines) of the fish. It was unclear whether the viscera were already removed in the study by de Graaf et al. (2016), on which the catch estimate for 2025 was based. Viscera makes up between 12 and 18 percent of the whole fish (Rustad et al., 2011; Torres et al., 2007). Using this, a range was established for the amount of product that needed to be processed per working day. The number of working days in a year was taken from RCN (2025). The fish monger provided an estimate of the amount of waste material resulting from a given number of fish.

To evaluate whether the materials were suitable as pet feeds the nutritional value of viscera was compared to the recommended nutrient intake for dogs and cats. Only viscera were evaluated, as the composition of the fishmonger's waste material was unknown. Data on the nutritional value of the viscera of common fish on Bonaire was not found. From a review by Rohim et al. (2024) the lipid, protein and ash contents of several seawater water fish could be derived. The average percentage of lipid and protein was then compared to the recommended lipid and protein intake for cats and dogs. They were compared as a percentage of dry weight. The recommended nutrient intake was based on nutritional guidelines by Fédération Européenne de l'Industrie des Aliments pour Animaux Familiers [FEDIAF] (2025). Although FEDIAF represents the European pet food industry, its guidelines are science-based and derived from established sources such as the National Research Council (NRC).

Economic feasibility assessment

The economic feasibility was determined using the waste material estimates derived from literature and the local fishmonger. The feasibility was assessed based on the profit generated per fisherman through fish waste recycling. This could be calculated using the amount of waste material, the price that could be asked for the pet feed created, and the cost of creating the feed. A graphical overview of the method can be found in Figure 14. The full calculation is provided in Appendix F.

First, the revenue per kilogram of pet feed sold on Bonaire was determined. The data used for this were taken from Fundashon Tienda pa Konsumidó Boneriano (2025). This is a government-backed non-profit organization that protects the rights of Bonairean consumers. They investigated the price of certain supermarket products on a monthly basis, using data from 21 supermarkets. Three months for which data could be accessed at the product level were selected. A full overview of the data is available in Appendix G. Using this, the average kilogram price for dog kibble, cat kibble, wet dog feed, and wet cat feed was established. From this, 8% tax (Caribisch Nederland Belastingdienst, 2025) was subtracted to determine the revenue per kilogram.

Two scenarios were then set up to determine the cost of processing the waste material: one in which an external facility was used for processing and one in which processing was done in-house and only an operator was paid. In both scenarios, machine payback, operating costs, and middleman costs were taken into account.

The operator cost was based on an 8-hour working day and the minimum salary on Bonaire of $1,794 per month (Eerste Kamer der Staten-Generaal, 2025). Machine payback was determined using a total equipment cost of $3,000 and a payback period of two years. It was assumed that 20% of the revenue would be used to pay a “middleman” to distribute the product after production.

The additional cost of the external facility scenario was determined using rent, insurance, and utilities. Rent was based on an active listing of a facility of 109 m². Electricity cost was calculated using kilowatt-hour pricing on Bonaire (Water- en Energiebedrijf Bonaire [WEB], 2024) and an electricity usage estimation based on a business of similar size and (CBS, 2019).

The cost of water was calculated using a water usage estimation of a similar business (van Berkel et al., 2022) and the water price on Bonaire (WEB, 2024). Insurance cost was based on current pricing for business liability and inventory insurance of a company and facility of this size (Rabobank, 2025a, 2025b).

The minimum profit and average profit per fisherman for both scenarios were then calculated. The minimum indicated whether the recycling was profitable in the most unfavourable case. The average profit gave an indication of the average profit to be made. For the minimum, it was assumed that the amount of fish to be processed was at its lowest within the range established in the section Catch quantities and waste. For the average profit, the average of the range was used.

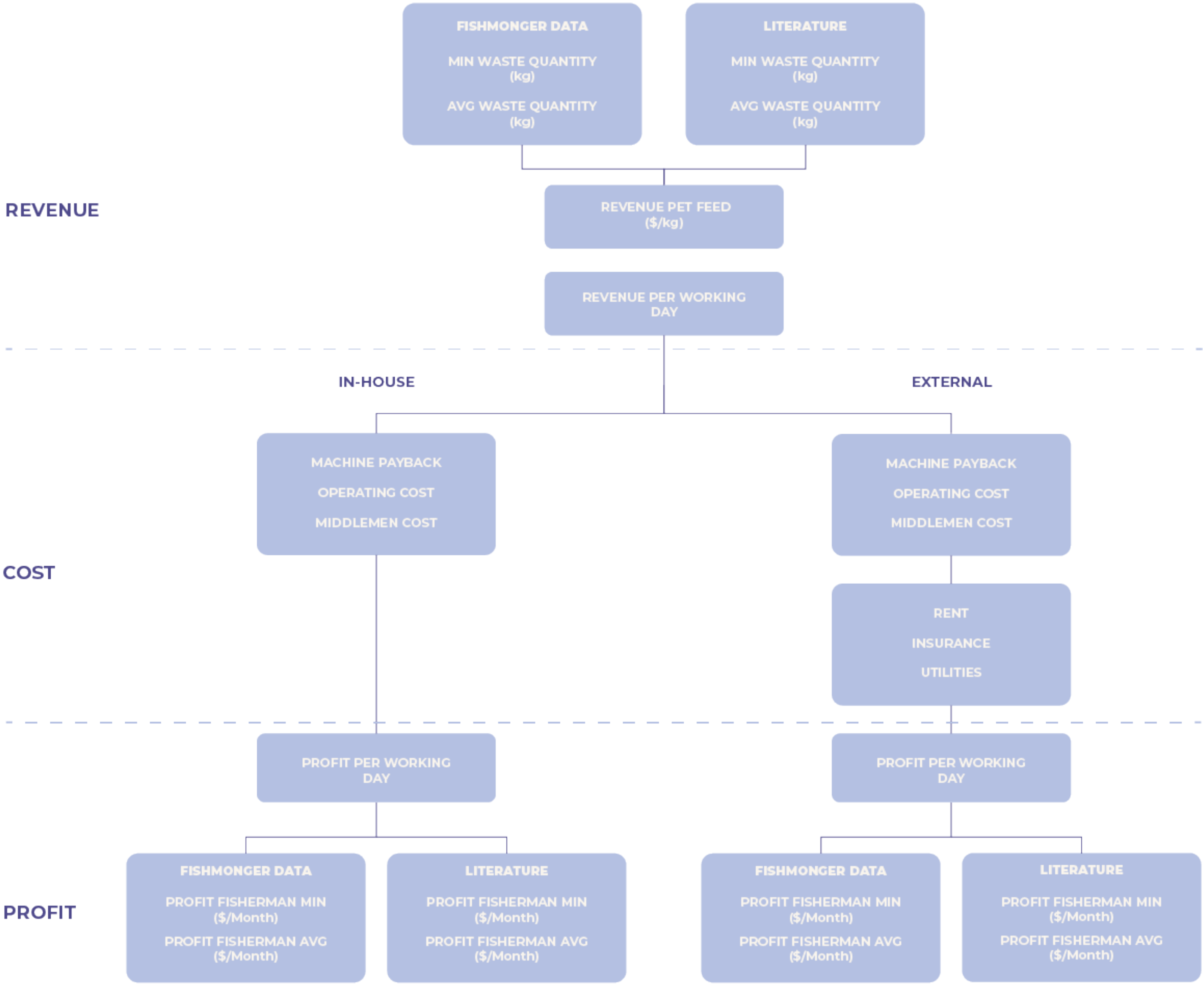


Figure 14. Graphical overview of the methodology used to calculate the profit of creating pet feed from waste material.

The profit per fisherman was then determined using the revenue per working day, cost per working day, and the number of fishermen. The revenue per working day was based on selling the most profitable feed type. The number of fishermen was based on the number of fishermen affiliated with PISKABON, the local fishing cooperative, which counted 45 members in 2020 (RCN, 2023).

The minimum and average profit per fisherman were also determined based on the data provided by the fishmonger. The revenue was based on the revenue per kilogram of the most profitable pet food type and the amount of material that could be transformed into pet feed. The amount that could be transformed into pet feed was based on the fishmonger's estimates of both the daily catch quantities and the waste percentage. The scenarios described previously were used: one involving an external facility and one in which processing was done in-house. Cost determination was performed using the same methodology as described previously. The profit per fisherman was calculated for both the external and in-house scenario, considering both the minimum and average quantities of fish received.

Design requirements

Findings from the Bonaire inventory were translated into requirements for an FRP-system for Bonaire. A requirement for the amount of waste to be processed per working day was established. Both the quantities established from literature and fish monger data were considered, as described in the section Catch quantities and waste. The estimation based on the fish monger data differed substantially from the literature-based estimation and most historical data. The waste quantity found using literature was therefore used in the requirement. The upper value in the range established in the literature assessment was chosen, as the system should be able to process a peak quantity. Evaluating the economic feasibility indicated a certain pet food type as most profitable. Several requirements regarding this feed type were added. The traceability as described in the introduction and background of the output of the system was also added as a requirement.

Designing an FRP-system

To design the FRP-system, components were first evaluated. Selected components were then combined into an FRP-system prototype for Blijdorp. Based on this prototype, a concept design for pet-feed production on Bonaire was developed. Components were sought to achieve three goals: feed stability in water, attainment of the required feed sizes and feed buoyancy. One component was developed, the agar cooling setup, which was designed to speed up the production process. Component testing and prototype construction were carried out in a laboratory setting at Blijdorp, whereas the concept for Bonaire was developed as a digital design.

Testing and evaluating components

Stability

Techniques were explored to create stable agar. Mixing techniques, heating techniques, and agar-to-water ratios were examined. Binding agar to fish residues was also investigated. First, manual binding of fish and agar was studied. Then, different impellers used to mix agar and fish residues were analysed. Each sample was assessed visually and tactilely.

Three mixing techniques for water and agar were explored: magnetic stirring, overhead mixing, and manual mixing. For each method, a 1000 ml glass beaker was filled with 400 ml water coming from a Quooker to which 20 g of agar (UNIQUE Agar) was gradually added. This ratio was based on the current recipe used at Blijdorp. For the magnetic stirring a stirring rod was added to the beaker and placed on a magnetic stirrer (Heidolph MR 3001 K; Heidolph Instruments GmbH & Co. KG, Schwabach, Germany). For the overhead stirring an overhead mixer (IKA Eurostar Power Control Visc; IKA-Werke GmbH & Co. KG, Staufen, Germany) and an angled four-blade impeller were used. Hand stirring was performed manually with a tablespoon.

Three agar-to-water ratios were tested to evaluate their impact on the firmness of the resulting agar blocks. The ratios were based on the recipe used at Blijdorp for recycled food making. They used 25 g of agar per litre of water. Two additional samples were made using 15 and 5 g of agar per litre ratio. The agar was dissolved in 200 ml of water in a 200 ml beaker using the magnetic stirring method. Each variation was poured into a takeaway (750 ml) container and left to cool down.

Induction cooking was tested as a heating method for creating agar. In the current recycling process at Blijdorp agar was boiled using a two-step process. It was attempted to replicate this in a single step. A stainless-steel pot was placed on an induction cooktop (Figure 15). In the pot 133 ml of water and 7 gr agar were mixed by hand using a spoon. The induction cooktop was then set to 100 °C and the liquid stirred intermittently. When the liquid began to boil the pot was removed from the induction cooktop. It was then left to cool until the agar had fully solidified.

The agar to fish residue binding of the current fish recycling method at Blijdorp was evaluated. The mixture was created under supervision of a senior caretaker. Fish residues, totalling 300 g, were blended smooth using an immersion blender. Agar, totalling 20 g was gradually added to a plastic beaker containing 400 ml of water from a Quooker while stirring using a fork. The beaker was microwaved for 1.5 minutes. The beaker was then placed in a plastic container filled with cold tap water, with a mercury thermometer inserted into the agar to monitor its temperature. One scoop (1 ml) of akwavit powder (Kaspar fauna food zoos specialities Akwavit) and two scoops of vitamin c powder (nova vitae Vitamine C L-ascorbinezuur poeder) were then mixed into the fish residues using a fork. Once the agar was cooled below 50 °C it was added to the fish residues and hand mixed with a fork. The mixture was then placed into a fridge and left overnight.

Three impellers were evaluated for mixing agar and fish residues-based on inspection of the vortex in water and the visual homogeneity of the mixture. A flat four-blade impeller, an angled four-blade impeller, and a spiral impeller (Figure 16) were evaluated.

Figure 15. Setup for agar making on an induction cooktop.

Figure 16: From left to right: four-blade flat impeller, spiral impeller and four blade angled impeller.

The impellers were placed in the overhead mixer and lowered into a glass beaker containing water. Agar–fish residue mixing was subsequently tested with two impellers. For each impeller 133 ml agar was prepared using magnetic stirring, to this 100 g of fish residues was gradually added. The mixer speed was set manually to achieve adequate mixing.

Shaping feed particles

Shaving, extruding and “spherification” were explored as techniques of creating suitable sizes of aquaculture feed. Shaving was first explored manually and later mechanically. Each sample created was assessed on its visual and tactile properties.

Manual shaving tests were performed using agar-only samples and agar–fish residue samples. Samples prepared to evaluate agar-to-water ratios, to test the mixing of agar and fish residues and to test induction cooking, were reused for shaving tests. Portions of the agar-to-water ratio-test blocks were frozen in a household freezer. All samples were then grated using a household grater, using both the coarse and fine sides. In addition, two agar–fish residue samples were prepared for shaving evaluation. They were made by preparing agar on an induction cooktop using 133 ml water and 7 g agar. To the agar 100 g of fish residues was added using an overhead mixer equipped with an angled four-blade impeller.

Mechanical shaving samples were created using an electric vegetable cutter (ALPINA 4-in-1 electric vegetable cutter, 200 W) and a Dynacube. Four agar samples were created using agar prepared on a cooktop. The first sample using 133 ml of water and 6.7 gr of agar, the second and third with 400 ml of water and 10 gr agar, the fourth with 400 ml water and 20 gr agar. The first sample was grated using the coarse drum of the vegetable cutter. The second sample was diced using the coarse dicer (17 mm) of a Dynacube, followed by coarse grating using the vegetable cutter. To make the third sample the agar was poured into the pushing rod (Figure 17) of the Dynacube to use it as a mould. Half of the sample was then sliced using the coarse dicer and half with the fine dicer of the Dynacube. Approximately half of the material from the fine dicer was then grated using both the coarse and fine grating drum on the vegetable cutter. The fourth sample was also produced using the moulding method, with 300 g of fish residues added. It was then sliced using the fine dicer on the Dynacube followed by coarse and fine grating on the vegetable cutter.

Extruded samples were created using a garlic press or potato ricer. Samples prepared to assess agar-to-water ratios were extruded using a garlic press. Samples created to test the mixing of agar and fish residues, were re-used and extruded using a potato ricer. In addition, one of the agar–fish residue sample containing fish residues that was previously used for shaving tests was extruded using the same method.

“Spherification” is the process of forming spheres from a material by rapidly cooling it in a liquid. Two sphere samples were created using an agar only, and a third sphere sample was created using agar and fish residues. For all samples, the mixture was dispensed dropwise using a 10 mL syringe with a 2 mm opening.

Figure 17. Pushing rod of a Dynacube used as a mould by filling it with agar.

The agar for the first sample was made using 133 ml water from a kettle and 7 g agar by hand stirring. When the mixture started to firm up, it was dispensed into a drinking glass filled to one quarter with sunflower oil at room temperature. The second agar sphere sample was created with agar prepared on an induction cooktop, using 133 mL of water and 6.7 g of agar. A drinking glass filled to three quarters with sunflower oil was cooled for one hour in a household freezer. When the agar started to stiffen, it was dispensed into the sunflower oil. An agar–fish residue sphere sample was made by mixing 66.5 ml of agar with 50 g of fish residues, prepared similarly to the shaving sample. A 250 mL plastic beaker was filled with 80 mL of sunflower oil at room temperature, which was not cooled as in the previous tests due to the absence of a freezer at the marine laboratory where the experiment was conducted. When the agar–residue mixture cooled below 50 °C, it was dispensed into the sunflower oil.

Buoyancy

Various methods were investigated to achieve buoyancy through introduction of air into the feed. The methods investigated included hand whisking, a handheld electric whisk, and an overhead mixer. Experiments were first conducted using an agar–water mixture, followed by trials with an agar–fish residue mixture. Samples were evaluated through visual and tactile assessment combined with buoyancy testing.

Two samples were made using hand whisking. A first sample was made by mixing 200 ml of water and 5 g agar using magnetic stirring. It was then whisked using a metal household whisk. The mixture was then placed in the fridge to solidify. The sample was sectioned to inspect for the presence of trapped air bubbles. A second sample was created by hand using 100 ml of water and 5 g of agar. The agar was then transferred to a steel bowl to cool down. When the agar began to solidify, it was hand-whisked with the bowl held at a 45° angle until it became too firm to continue.

Three samples were made using a handheld electric whisk. The first sample was made by hand mixing, using 100 ml of water and 5 g of agar in a 500 ml plastic beaker. The whisk was first inserted when the mixture was fully liquid. The mixture was whisked until a foam layer started to form on the surface. The solution was whisked a second time just before it started to solidify. The mixture was then left in the fridge to solidify. A second agar sample was created on an induction cooktop using 133 ml of water and 6.7 g of agar. The mixture was left to cool down till it nearly solidified. The whisk was then inserted to aerate it. Finally, it was placed in the fridge.

For the samples created by overhead mixing the mixer was set up as seen in Figure 18, with the coil of the electric whisk inserted. First three samples were prepared using only agar. The agar was prepared on an induction cooktop. The first two samples were made with 133 ml water and 6.7 g agar, for the third 3.35 g agar was used. In the first sample, the coil was placed in the mixture, just before it started to solidify. The pot was held at a 45° angle and the mixer set to a speed of 2000 rpm. The mixture was then left in the fridge to solidify. Buoyancy testing was then conducted using a small cube (+/- 10 × 10 × 10 mm). Subsequently, shavings produced using the coarse side of a hand grater were evaluated. For the second sample the same process was followed, except attempting the whisking at a later stage. For the third sample coil was inserted when the agar barely started to solidify and was whisked until a foam layer was formed on the surface.

Figure 18. Overhead mixer fitted with whisking coil to aerate agar.

When the mixture was almost completely solidified the coil was inserted again. Buoyancy testing was then performed with a piece of about 20 x 10 x 5 mm. Subsequently shavings grated using both the coarse and fine side of the hand grater were tested.

Two agar–fish residue samples were aerated using overhead mixing. The agar was prepared on an induction cooktop using 133 mL of water and 3.35 g of agar. The mixture was then aerated using the same method as for the agar-only samples. For the first sample, aeration was applied for one minute and 15 seconds prior to solidification, this was repeated for two minutes once solidification had begun. For the second sample, aeration was applied for one minute and 20 seconds at the onset of solidification. In both samples, 50 g of fish residues were subsequently added gradually by manual mixing. The samples were then placed in the refrigerator to solidify.

Automated agar making

A single setup was designed to perform both agar cooking and cooling, after which the prepared agar was maintained at 50 °C (Figure 19). This temperature was specified in the requirements. This setup was automated using a microcontroller. It was evaluated by examining the properties of the agar and by monitoring process temperatures. Initial tests were performed with cooking, cooling, and holding. Subsequently, tests were performed with cooling and holding only.

The setup consisted of a heated stirring plate and an overhead mixer. A pot was positioned on the stirring plate. Inside the pot a temperature probe (DS18B20) was placed. The temperature probe communicated temperature readings to a microcontroller (Arduino Uno Rev3 - ATMEGA328). The microcontroller was connected to two one channel relays (SRD-05vdc -sl-c). The relays were configured in a normally open state. One relay controlled the low-voltage circuit of the stirring plate, allowing it to be switched on and off by the microcontroller. The other relay controlled the 230 V mains supply to the mixer, used for stirring. A target temperature could be set using the programme on the microcontroller. The controller would then try to achieve the target temperature through hysteresis control. A threshold could be set if the temperature measured by the probe fell below target temperature minus the threshold, the heated plate would be turned on. Likewise, when the temperature came above target temperature plus the threshold, the heater would be turned off. Intervals could also be set for the mixer to turn on and off. The program also generated a graph of the temperature readings. An overview of the system can be found in Figure 20. The code of the programme was specifically developed for this study and can be found in Appendix H.

The first two tests were performed to integrate cooking, cooling, and holding. In the first test, cooking followed by temperature holding was evaluated using 400 ml of cold

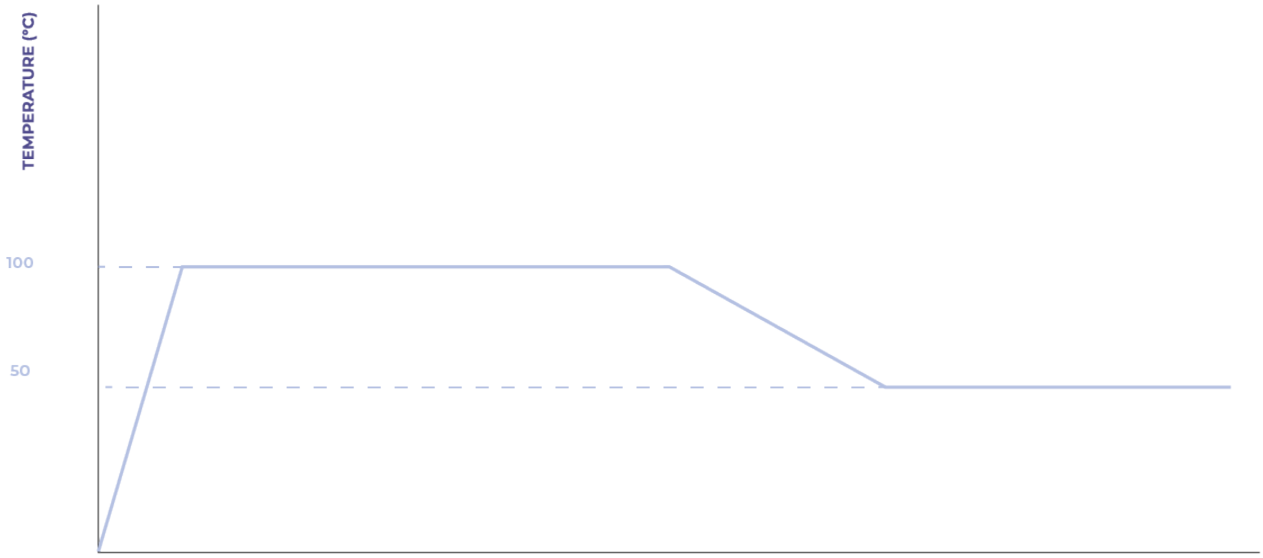


Figure 19. Graphical representation of cooking, followed by cooling and holding at 50°C.

tap water with 20 g of agar. The heated plate and target temperature were initially set to 100 °C with a 2 °C offset. The liquid was intermittently stirred by hand, and a lid was added after 6 minutes to improve heating. After 27 min, the heated plate temperature was increased to 175 °C. At 35 min, the target temperature was reduced to 50 °C, and after one hour it was further lowered to 47 °C. In the second test, cooking and temperature holding were combined in an automated program using 400 ml of cold tap water with 20 g of agar. The heater was set to 175 °C. The program maintained a target temperature of 83 °C for 3 min before lowering it to 47 °C with a 2 °C offset. A lid was kept on the pan throughout the test, except during manual stirring. Manual stirring was performed every 5 min initially and every 2.5 min after the first 5 min.

Four tests were performed to investigate cooling and holding, first using water, then using water and agar. For the agar test, the agar was prepared on a cooktop plate. The induction cooktop was set to 120 °C and the agar water mixture was heated for 2 minutes and 30 seconds. The settings for these tests can be found in Table 1.

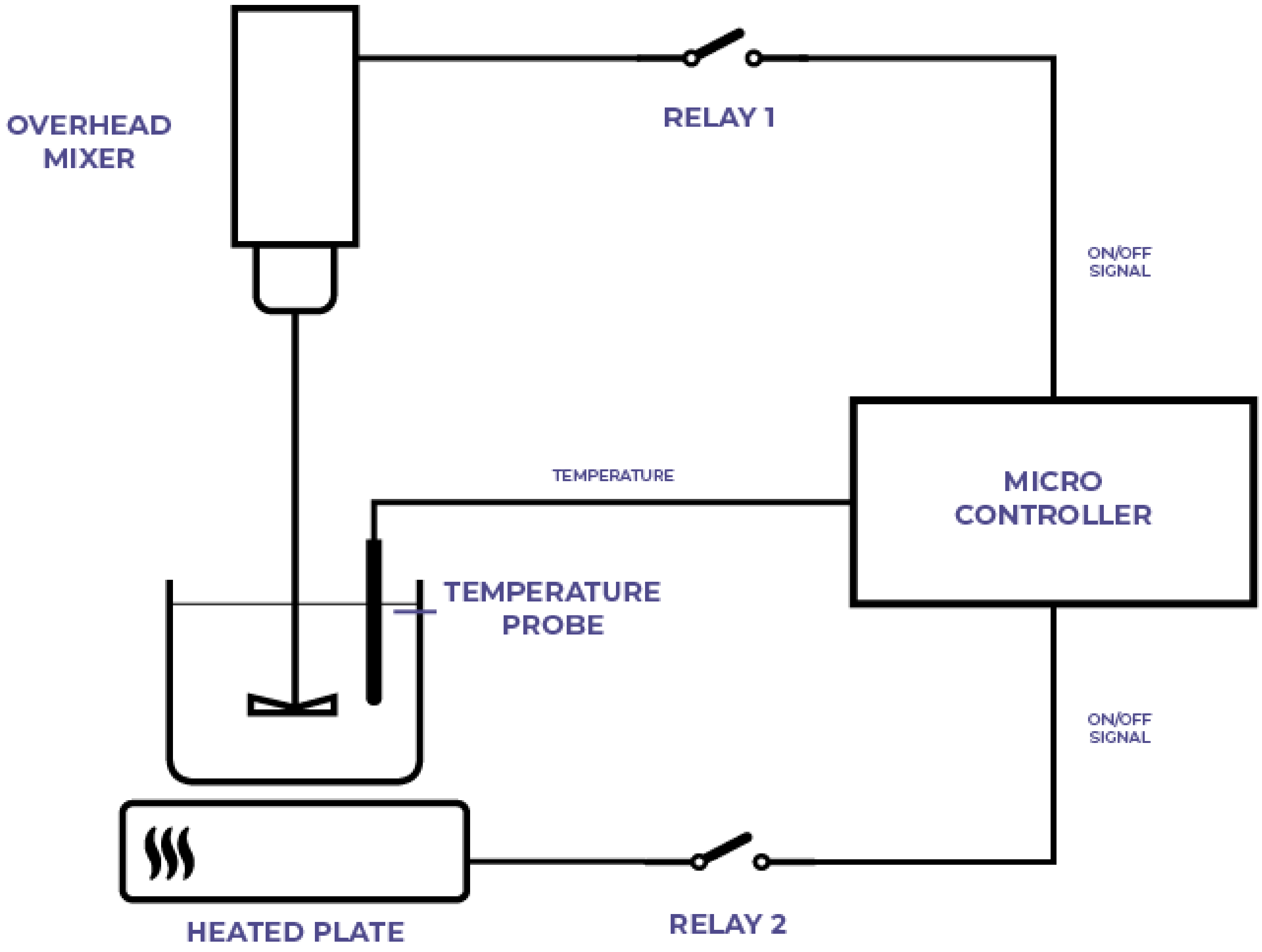


Figure 20. Graphical overview of the operating principle of the automated agar cooling setup

Liquid type	Water (ml)	Agar (g)	Stirring plate temperature (°C)	Target Temperature (°C)	Offset (°C)	Plate Temperature Adjustments	Stirring
Water	400		125 °C	50	2	None	Intermediate manual
Water	400		80 °C	50	0.2	75 °C, 55 °C, 51 °C	Intermediate manual
Water	400		51 °C	49	0.2	None	Overhead mixer, Every 1 min, 15 s, 50 rpm
Water + agar	400	20	51 °C	49	0.2	None	Overhead mixer, Every 1 min, 15 s, 50 rpm

Table 1. Overview of settings for the four temperature holding tests.

FRP-system prototype Blijdorp

A prototype system was set up using effective components found using the methods described in the section Testing and evaluating components. The setup was evaluated by a walkthrough with a senior caretaker, comparing feed properties to the requirements and by evaluating the production capacity.

The prototype system was evaluated by a senior caretaker through observation of a system walkthrough, followed by a structured interview. During the walkthrough, the caretaker was asked to observe closely and make notes where needed. First, the process of making agar was demonstrated. While the agar was cooling, the steps to acquire the required feed particles were demonstrated. This was done using an agar–fish residue sample that had been prepared two days prior to the walkthrough. A pre-made sample was used because the material needed time to solidify in the refrigerator, and there was insufficient time to complete this process during the walkthrough. Once the agar had cooled, the mixing of agar and fish residues was demonstrated. Afterward, the interview was conducted. Full records of the interview can be found in Appendix I.

The properties of the feed were compared to the requirements. The feed created during the walkthrough was used to do this. The feed sizes created were measured using callipers. These measurements were compared to the sizes of current dry feeds, which were documented as described in the section Feed usage and waste materials. The stability in water was then evaluated by immersing the feed in water.

The production capacity was determined by calculating the time needed to produce one kilogram of the feed. During the walkthrough and during testing of system components, the duration of process steps was recorded. Only steps that required operator involvement were considered. Using this, and the amount of input materials the production capacity was determined. This value was compared to the value determined in the requirements to make the process economically feasible.

Concept of FRP-system Bonaire

An concept of an FRP-system for Bonaire was developed using the requirements set up in the Bonaire inventory and the prototype FRP-system for Blijdorp. The concept was evaluated by making an estimation of the cost price.

The concept of an FRP-system for Bonaire was created by scaling the system components proven to work for Blijdorp. This was done to accommodate the higher processing output needed on Bonaire.

Using the ratios for waste recycling and the requirement on the processing capacity, it was determined how much agar, water and fish residues were needed per batch. Using this total, a processing vessel was chosen. A standard size pot was selected that could accommodate this total with headroom left. Alongside the pot a compatible heating source was chosen. To effectively heat the larger volume, the version delivering the maximum power available from a 230 V socket was selected. For the blending of fish waste a standard size pot was also selected.

For mixing and blending, off-the-shelf components were chosen that operate using a similar working principle to those used in the Blijdorp prototype. For the blending component the amount of fish waste that had to be processed per batch was considered. For the mixing of agar and water and subsequent mixing of agar and fish residues the impeller size and design were important. Heating, cooling and mixing of materials needed to be performed for a mixture of high viscosity. Off-the-shelf impeller designs were evaluated accordingly using a study by Salho & Hamzah (2024). The results of mixing tests for the Blijdorp FRP-system were also taken into account. Considering this an off-the-shelf mixing system was selected.

Based on the concept of the automated cooling and holding system for the Blijdorp prototype an automated cooling and holding system was designed for Bonaire. For holding the liquid at 50 °C, a hysteresis system could be used, just like at Blijdorp. When the temperature drops below 50 °C, heating would start. In the Blijdorp prototype the agar was cooled down from the boiling temperature to 50 °C through convection to the surrounding air. It was assumed that cooling using convection was not sufficient to achieve the required cooling time. The reason for this was the higher volume of the material and the higher ambient temperature on Bonaire, which was 29 °C on average (timeanddate, n.d.). A cooling system was designed to aid in cooling the agar to 50 °C.

To get the correct feed particle size a pouring and slicing system was designed. Because of the higher weight of the agar-fish-residue mixture it was assumed that the product could not be poured by hand. A frame was designed that enabled the pouring of the mixture. The frame could also support the weight of the equipment needed for mixing. In the frame a mechanism was implemented that ensured that the heating source did not carry the full weight of the system. In the frame a counterweight was also integrated to ensure the system would not tip over when pouring. Using the standard weight of wet dog food sold on Bonaire a cutting tool was designed to create the correct portion sizes.

To validate the concept the approximate cost price was compared to the price used in the economic feasibility assessment. The cost price of parts was based on the purchase price of components when sourced from the Netherlands. The production cost of custom-built parts was estimated. The whole approximation was based on the production of one unit.

RESULTS

RESULTS

Inventory and requirements

Blijdorp

Feed usage and waste materials

A variety of dry fish feeds were administered at Blijdorp, with feed type mainly determined by fish size and feeding behaviour. Three forms of dry feed were used: sticks, pellets, and flakes (Figure 21). Larger species, such as sharks and rays, were not fed dry feed, whereas smaller species, such as batfish, received dry feed. Feed size was selected based on fish size: flakes were primarily consumed by smaller or younger fish, while pellets and sticks were intended for larger fish. A specific large pellet produced by Alltech Coppens was fed exclusively to the sturgeon three times per week. The feed types and their associated sizes can be found in Table 2. Feeding position within the water column varied by species, with some species, such as sturgeon, feeding near the bottom, while others fed in mid-water or near the surface. To accommodate these behaviours, floating, semi-floating, and sinking aquaculture feeds exist. At Blijdorp, sinking feed was preferred due to the water filtration system. In all cases, the feed had to be stable in water, so the nutrients did not dissolve. Based on these findings, requirements 2, 3, and 4 were defined (see section Design Requirements).

During a feeding routine, approximately 215 g of dry feed were administered, with feeding practices varying according to fish size and stocking density. In tanks with larger or more numerous fish, flakes, pellets and sticks were distributed by the handful, whereas in tanks with smaller fish the flakes were pinched between the thumb and index finger. When multiple feed types were used, feeds were either mixed together in a container prior to distribution or first placed in a beaker of water. Feeding was performed incrementally to allow caretakers to monitor fish responses, prevent overfeeding, and ensure that all individuals had access to food.

Waste was generated from feeding fresh frozen fish. A standard diet was provided, while the feeding behaviour of the fish was highly variable. Especially after the feeding of sharks, there was leftover material. The sharks were trained to swim to a specific spot at the edge of the tank, where they were offered food using long sticks that could be lowered into the water. They had learned to recognize the splash of the sticks as a feeding signal and approached to collect their food. For 15 minutes, pieces of fish were placed on the sticks and offered to the sharks. After this period, feeding ceased and the remaining material was collected.

Type	Size (mm)
Flake	2 x 0.2
Small pellet	1 x 1
Stick	10 x 3
Medium pellet	3 x 3
Sturgeon pellet	9 x 12

Table 2. Dry aquaculture feed types and sizes in use at Blijdorp.

Figure 21. From left to right: pellets, sticks and flakes.

The remaining material was offered to the caretakers of the mammals; occasionally, they could use the leftovers. A portion of 300 g was recycled into wet feed to be administered the next day. Materials that ultimately were not used were disposed of in the trash. A similar material flow applied to other fish that were fed with fresh fish.

Waste was also generated during the preparation of fish meals. In the fish kitchen, meals for specific species were prepared each morning by a single caretaker. Ingredients used for the meals were kept in a container sized freezer. A day in advance the ingredients needed were moved to a similarly sized defrosting chamber to defrost. When a meal was prepared ingredients were taken from the defrosting chamber. Using a recipe book present in the kitchen the meals for each species were then prepared (Figure 22). This was done through cutting the ingredients to bite-size pieces and weighing them. The completed meals were then put in a stainless-steel container per species. The containers were put on a rolling cart for another caretaker to collect and use to distribute the meals (Figure 22). Once this process was completed some material was left over because it was difficult to thaw the exact amount of material that was needed. A complete overview of the material streams, including waste, at the Oceanium can be found in Figure 23.

Figure 22. Meal preparation in the fish kitchen (top) and meals ready to be distributed (bottom).

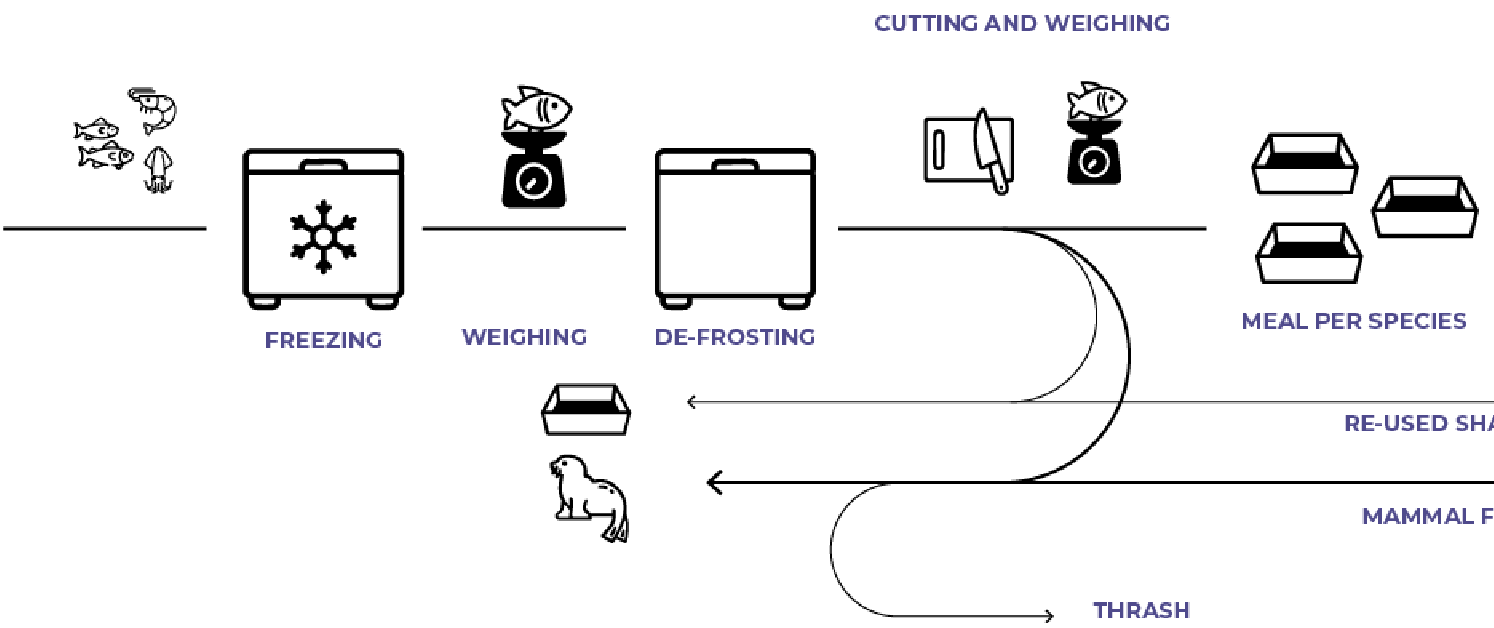


Figure 23. Graphical overview of material streams.

On average, 8 kg of waste material was generated per week from feeding. The total amount of waste material from feeding in 2024 was 413 kg. This represented 8% of the total 5186 kg fed in 2024. On Mondays, Wednesdays, and Fridays the most waste was created on average (Figure 24). These were all days on which sharks were fed. The contribution of waste from shark feeding was the largest, accounting for 63% of the total amount of waste material generated. Based on these findings, requirements 1 and 5 were defined (see section Design Requirements).

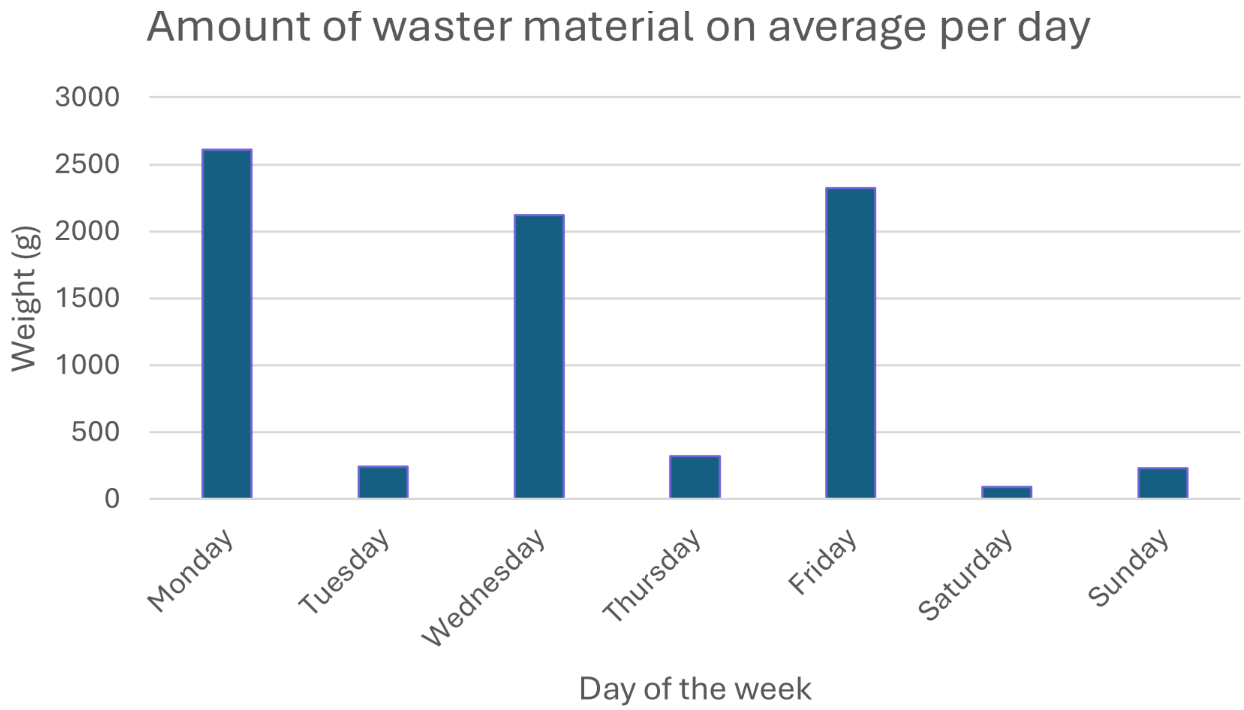
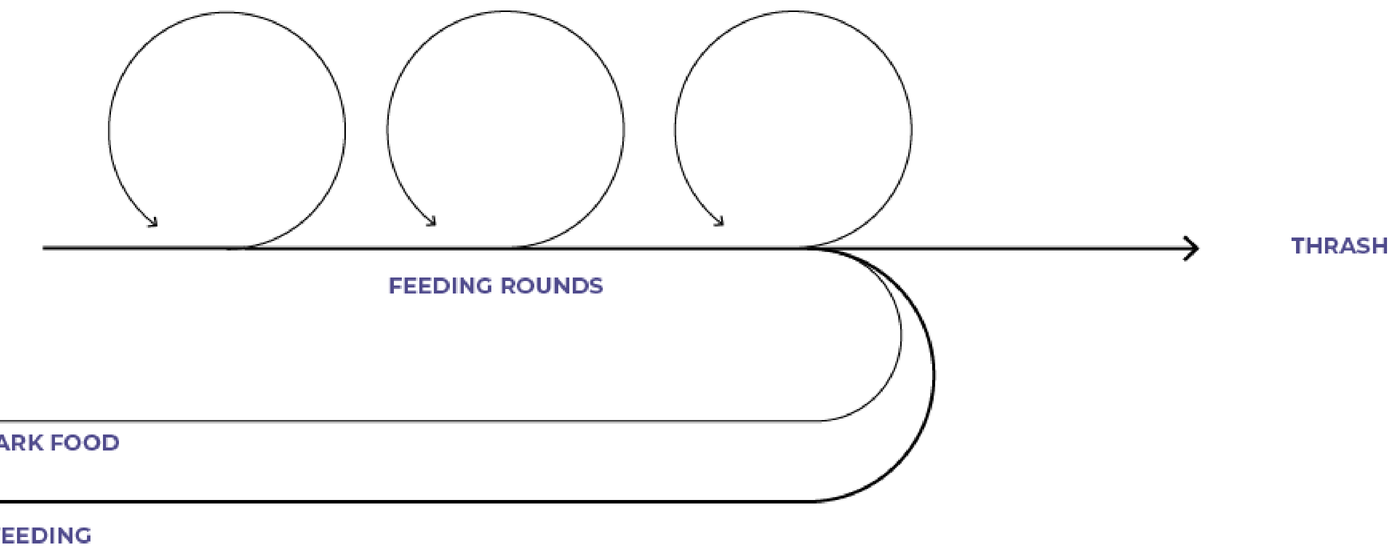


Figure 24. Average amount of waste material per day of the week.



In the current waste material recycling process at Blijdorp, a gel-like block (Figure 25) was created by binding fish residues with agar. An overview of the process can be found in Figure 26. First, approximately 300 g of fish residues left over from feeding the sharks were collected. Then 400 ml of boiling water was taken from the Quooker. Into this water 20 g of agar was mixed by hand. This agar was then placed in the microwave for 1.5 minutes until a foamy layer formed, indicating that the material had thickened. The agar was then cooled in a water bath to below 50 °C, which took approximately 15 minutes. The temperature was checked with a mercury thermometer. This was done because nutrients would be damaged if the fish residues came into contact with agar at a higher temperature. This temperature was also chosen because it lies slightly above the gelling temperature of agar. While the agar was cooling down, the fish residues were blended with a handheld immersion blender. In general, longer blending produced a more homogeneous paste, but a balance was kept between time and smoothness. Once blended, vitamin C and Akwavit powder were mixed in by hand. These were added because vitamins and minerals degrade when fish are stored in the freezer for a prolonged period of time. When the agar had cooled sufficiently, it was poured over the fish mixture and stirred thoroughly by hand before being refrigerated to solidify. The gel was kept in the fridge overnight. The next day it was cut into pieces for serving. The process was performed on Mondays, Wednesdays, and Fridays, as these were the days the sharks were fed and sufficient rest material was available. Based on these findings, requirements 6, 7, 8 and 9 were defined (see section Design Requirements).

Figure 25. Gel block created by binding fish residues to agar.

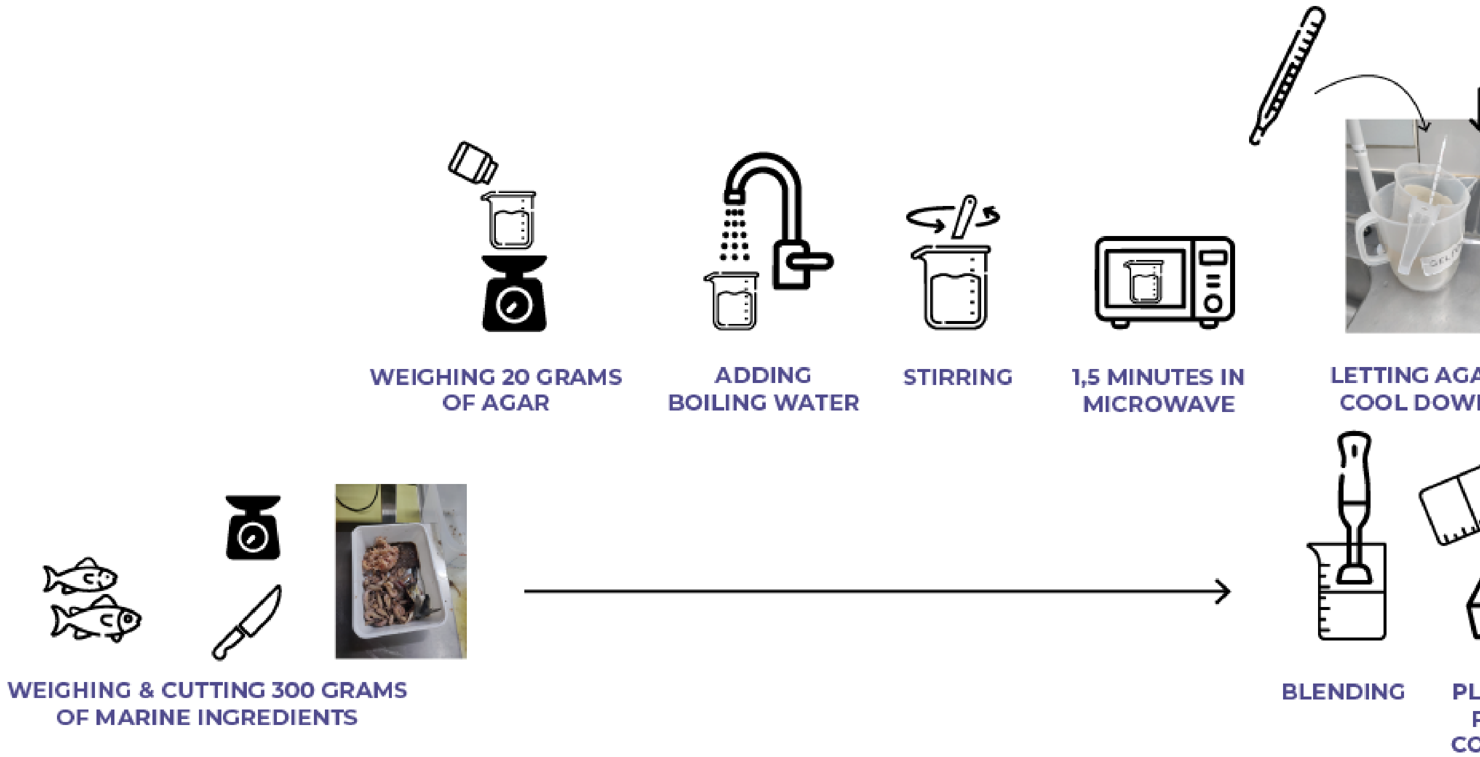


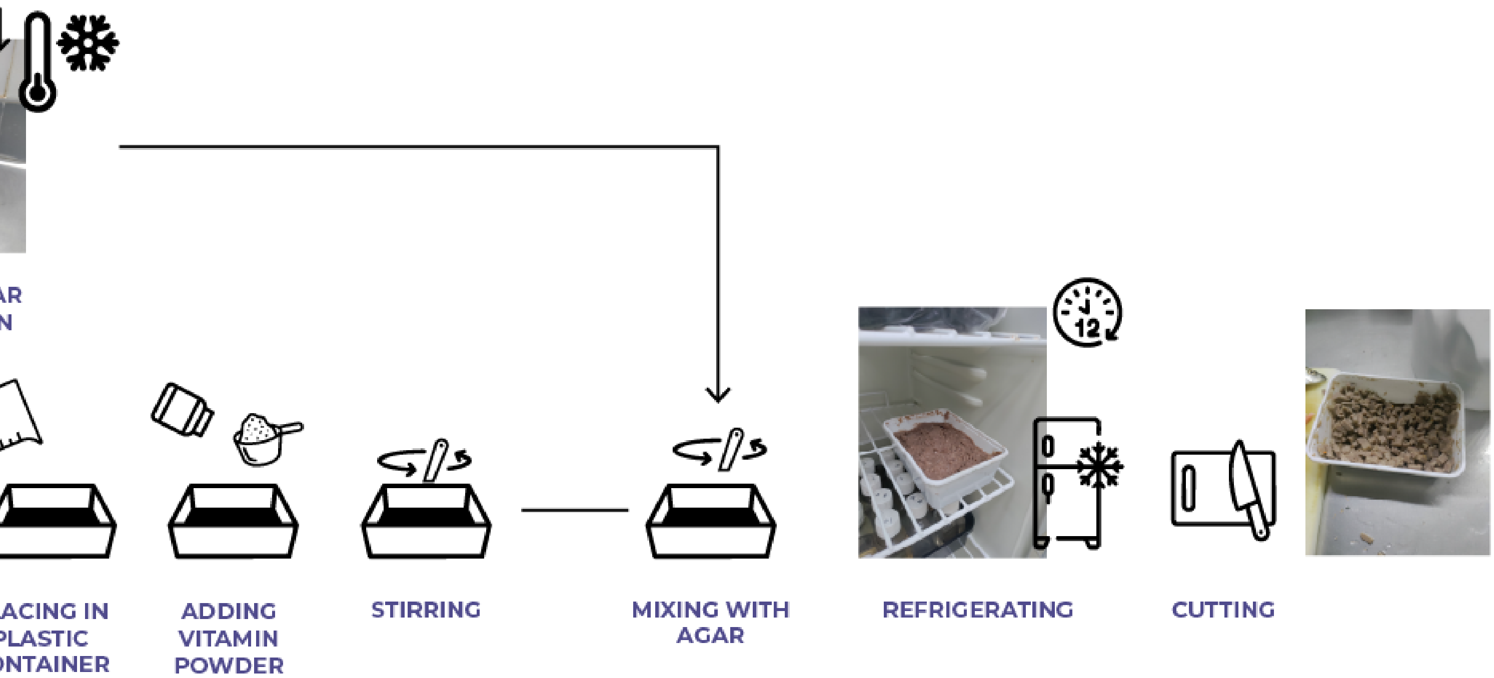
Figure 26. Graphical overview of fish waste recycling process performed at Blijdorp.

Economic feasibility assessment

The total amount of dry feed equivalent that could be created with the residues from feeding was 158 g per day. The total amount of wet waste product generated per year was 413 kg. The wet to dry conversion ratio was established at 0.14. The amount of dry equivalent per year was 57.82 kg, resulting in 158 g per day. This was 73% of the total 215 g needed.

The amount of time that could be spent on creating one kilogram of wet feed was determined to be 21 minutes. The price of dry feed pellets (Ocean Nutrition Formula One) was €63.60 per kilogram. Given a daily requirement of 215 g of dry feed, the total cost of purchasing the dry feed amounted to €13.67 per day. The dry matter content of the wet feed was 14.2%, a total of 1.51 kilograms of wet feed was needed daily.

The cost of producing the wet feed primarily consisted of machinery payback and labour expenses. Assuming the machinery costs €1,500 and a payback period of two years, the daily payback was €2.05. This left €11.62 available to spend on labour costs. With an hourly rate of €22.30 (including 30% overhead), the maximum allowable labour time for producing one kilogram of wet feed was 0.34 hours, or approximately 21 minutes per kilogram. Based on these findings, requirements 10 and 11 were defined (see section Design Requirements).



Design requirements

Requirements and the wish for the FRP-system for Blijdorp can be found in Table 3. The total amount of waste of 413 kg per year resulted in 8 kg of waste material to be processed per week (Requirement 1). The use of different feed sizes, as described in the section Feed usage and waste materials, and their water-stable behaviour were translated into Requirements 2 and 3. Requirement 4 was added to enlarge the applicability of the feed in aquaculture, although it was not a requirement for Blijdorp. To enable recycling of all waste generated, as discussed in Feed usage and waste materials, all marine ingredient types used at Blijdorp needed to be processed (Requirement 5). In the existing recycling process, the fish was exposed to a maximum temperature of 50 °C to preserve nutrients. This low temperature should also help preserve DNA quality, aiding traceability (Requirement 6). The existing shelf life of the feed was also adopted, which was one day (Requirement 7). It was also observed that agar and fish residues were mixed thoroughly and that vitamin and mineral powders needed to be added, this was captured in Requirements 8 and 9. The time required to produce one kilogram of feed was rounded down to 15 minutes from the 21 minutes calculated in the section Economic feasibility assessment (Requirement 10). Requirement 11 also originated from this, as operator cost was the main cost driver for in-house recycling and additional operators would increase costs. The aim of the FRP-system for Blijdorp was to replace dry feeds with the output of the system. Therefore, Requirement 12 was added, stating that the feed had to have at least the same nutritional value as the dry feed.

Number	Description	Derived from topic
1	The system can process at least 8 kilograms of waste material per week.	Waste stream quantification
2	Provides bite-sized formats suitable for all fish species	Dry feed usage and quantities
3	The produced feed does not dissolve immediately in water.	Dry feed usage and quantities
4	The system can produce both buoyant and non-buoyant feed.	Dry feed usage and quantities
5	The system can process all types of marine ingredients currently used at Blijdorp.	Identification of waste streams
6	No heat above 50 °C is introduced to the fish residues,	Re-using waste material
7	The product has a minimum shelf life of one day under refrigerated conditions.	Re-using waste material
8	The system must produce feed with a homogeneous composition.	Re-using waste material
9	The system allows homogeneous mixing of materials (residues, agar, vitamins, minerals).	Re-using waste material
10	The production of one kilogram of wet feed must not take longer than 15 minutes.	Economic feasibility assessment
11	The system can be operated by a single operator.	Re-using waste material, economic feasibility assessment
12	Produces feed with at least the same nutritional value as the current dry feed.	Background
13	The product must be traceable to the original species using DNA analysis.	Background
14	The product has a higher nutritional value than the current dry feed.	Background

Table 3. Design requirements for an FRP-system at Blijdorp.

The overall aim of the study was to create traceable feed, therefore, the feed had to be traceable back to its origin (Requirement 13). A wish was also added to create a feed with a higher nutritional value than the dry feed (Wish 14).

Bonaire

Catch quantities and waste

The annual catch quantity was estimated at 86 tonnes based on literature. Based on fishmonger data this was between 152 t and 380 t. The associated amount of waste material suitable for conversion into pet feed ranged from ~41–74 kg per working day based on literature values, and from ~180–450 kg based on fishmonger data. The nutrient composition of the waste material was also investigated and found to be higher than the recommended intake for pets.

The total fish catch quantity in 2025, based on literature, was ~ 86 t. The catches were estimated at 154 t in 2012, 102 t in 2014 and 147 t in 2020. A study by Schep et al. (2012) determined the average income of fishermen at ƒ35.511 or $19838. From Johnson (2011) it could be derived that there were 54 fishermen on the island and that the average catch price was $6.95. Dividing the income by the average fish price and multiplying the result with the number of fishers resulted in a total catch of ~154 t. A study by WWF (2020) estimated 30 to 40 fishermen present on the island, an average of 35 was used.

Eight fishermen interviewed estimated a combined catch of 33720 kg. This was 4215 kg on average per fisherman. This resulted in a total catch of ~147 t for all fishermen. A study by de Graaf et al. (2016) found the total fish catch over 2014 to be 102 tonnes after a 12-month survey. The study also reported the catches between 1908 and 2010 (Table 4), they varied between 80 tonnes and 200 t. It also revealed that through 12-month surveys resulted in 110 t (1908) and 90 t (2012) respectively.

The catch amounts reported for 2014 by De Graaf et al. (2016) were assumed to be correct due to the recency and thoroughness of the investigation, in line with recent news reports of declining catches. To estimate the total fish catch for 2025 it was assumed the catch on Bonaire followed the general trend of the area. The trend of the area was described by $M_{fish} = 4.876 \times 10^9 \cdot t^{-31.349}$
Here M_{fish} denoted the total annual catch quantity (kg) with t expressed in years. This yielded: $\frac{M_{fish}(2025)}{M_{fish}(2014)} = \left(\frac{2025}{2014}\right)^{-31.349}$

The catch ratio between 2014 and 2025 was 0.84, this resulted in an estimated 86 t of catch in 2025.

Period	Total Annual Catch (t)	Boat-based fishery		Shore-based fishery	Method
		Large boats	Small boats		
1908	110 t*	110 t	-	-	12-month survey
1956	140 t	140 t	-	-	survey?
1968	100 t	100 t	-	-	extrapolation 3-month survey
1978	160 t	160 t	-	-	survey?
1984	80 t	80 t	-	-	survey?
1973–1985	200 t	200 t	-	-	extrapolation 1 fishing boat
2010	160 t	-	160 t	-	literature
2014	102 t	60 t	30 t	12 t	12-month survey

Table 4. Historic fish catch quantities between 1908 and 2014.

The total catch quantities based on the data from the fishmonger were between 152-380 t annually (Table 5). The fishmonger estimated the daily amount of catch received to be between 200-500 kg per day. This was one of three fishmongers on the island. Assuming that every fish monger received an equal quantity of fish and 253 working days per year the total annual catch was between 152 t and 379 t. This was ~80% and ~340% higher, respectively than the estimations based on literature.

The estimated amount of waste material available for recycling ranged from 41-74 kg per working day based on literature values, and from 180 -450 kg per working day based on fishmonger data. Based on literature, the lowest waste amount occurred when the viscera fraction was 12% and the fish were not gutted, corresponding to 12% of the total catch. The highest waste amount occurred when the viscera fraction was 18% and the fish had been gutted. In this case, the amount of viscera was calculated as

$$\frac{18}{100-18} \times M_{fish}$$

resulting in approximately 22% of the total catch. The fishmonger estimated that approximately 30% of the delivered fish became waste, with three fishmongers present, this resulted in 180–450 kg of waste material per working day. Based on this, requirement 1 was defined (see section Design Requirements).

The average protein and lipid percentages in viscera (Table 6) were higher than the recommended intake for both cats and dogs (Table 7). The lipid content was about seven times too high for dog food and the protein content was twice as high. For cat food, the lipid content was four times too high, and the protein content was 50% too high. Based on this, requirement 7 was defined (see section Design Requirements).

Economic feasibility assessment

Processing rest materials into pet food was most profitable when it was sold as wet dog food (~$11/kg). Based on the average amount of fish waste available, as deduced from literature, the profit per fisher would be ~$150 per month. When instead the quantities estimated by the fishmonger were used, this increased to an average of ~$720 per month. Even when processing only the minimum determined quantities of fish waste, this still resulted in a monthly profit of ~ $90 (based on literature) and ~$560 (based on data from the fishmonger).

Fish delivered to the monger (kg per day)	Annual catch (kg)
200	151800
300	227700
400	303600
500	379500

Table 5. Fish amount delivered to the fishmonger and the associated annual catch for Bonaire.

Type	Protein (% DW)	Lipid (% DW)
Dog	18 - 21	5.5
Cat	25 - 33	9

Table 7. Recommended protein and lipid intake for cats and dogs as a fraction of feed dry weight.

Species	Scientific name	Protein (% DW)	Lipid (% DW)	Ash (% DW)
Rainbow smelt	Osmerus mordax	68.69	26.20	2.76
Atlantic salmon	Salmo salar	27.68	70.15	3.35
Yellowtail kingfish	Seriola lalandi	30.8	65.79	3.24
Yellowfin tuna	Thunnus albacares	70.86	16.74	14.7
Gilthead sea bream	Sparus aurata	23.76	61.86	2.25
Round sardinella	Sardinella aurita	23.69	40.26	5.66
Salema porgy	Sarpa salpa	76.76	16.65	17.38
Common cuttlefish	Sepia officinalis	26.23	10.01	21.27
Average		43.56	38.46	8.83

Table 6. Protein, lipid, and ash as fractions of the dry weight of seawater fish viscera

In these estimates, it was assumed processing could take place in-house.

The revenue per kilogram of pet food on Bonaire ranged between $3/kg and $11/kg (Table 8). This was calculated by subtracting tax from the average supermarket price. The highest profit was achieved by selling wet dog food, which yielded 104% more profit than the next most profitable food type. Based on these findings, requirements 6 and 7 were defined (see section Design Requirements).

Using the revenue per kilogram and the waste quantities deduced from literature the revenue per working day was determined. The profit was then determined by deducting the costs. A full overview can be found in Table 9. A distinction was made between the minimum quantity (41 kg /day) and the average quantity of fish waste to be processed (58 kg/day). A distinction was also made between in-house processing and processing in an external facility. The profit per fisherman per month was ~$90 (in-house) and ~$45 (external) at the minimum waste quantity. At an average waste quantity, this was ~$150 and ~$107, respectively. The profit from external processing was lower because more costs were deducted.

The operating cost that was deducted from the revenue for both in-house and external processing was ~$114. The additional cost for external processing was ~$135. The operating cost consisted of the operator cost, machine payback cost, and middlemen cost. The operator cost was established at ~$110 per working day. This was based on a monthly salary of $1,794, a 30% employer overhead cost, and an 8-hour working day. The machine payback cost per working day was ~$6. The cost of a middleman to distribute the product was estimated at 20% of the revenue. The main additional cost for external processing was renting the facility at ~$ 96.

In a similar manner, the profit per working day was determined based on the data from the fishmonger. For an average quantity of residual waste (225 kg), the profit was ~$720, and for the minimum quantity (180 kg) ~ $560, when processing in-house. For external processing this was ~$770 and ~$600.

Type	Price/kg ($)	Revenue/kg ($)
Non-branded dog kibble	3.68	3.41
Non-branded cat kibble	4.51	4.18
Non-branded wet dog food (canned)	11.79	10.92
Non-branded wet cat food (canned)	5.77	5.34

Table 8. Average pet feed supermarket prices and associated revenue.

Parameter	Minimum	Average
Waste material (kg/day)	41	58
Revenue ($/day)	443	627
Operating cost ($/day)	114	114
Middleman cost ($/day)	89	125
Additional cost external facility ($/day)	135	135
Profit fisherman in-house ($/month)	88	150
Profit fisherman external facility ($/month)	45	107

Table 9. Cost structure and profit overview.

Design requirements

Requirements on an FRP-system to create pet feed on Bonaire can be found in Table 10. Requirement 1 was calculated from the 74 kilograms that had to be processed at most per working day, resulting in ten kilograms of waste per hour. The economic feasibility analysis showed that the system was profitable when operated by a single operator (requirement 2). The overall aim of the study was to create traceable feed, therefore, the feed must be traceable back to its origin (requirement 3). It was estimated that residents on Bonaire would go shopping at least once a week, and that the food should therefore have a shelf life of one week (requirement 4). Requirements 5 and 6 were defined, because it was most profitable to sell the product as dog feed. Requirement 7 was established because it was found that the lipid and protein contents in the residual material were much higher than the recommended nutrient intake for dogs.

Designing an FRP-system

Testing and evaluating components

Stability

Agar prepared on an induction cooktop formed firm, water-stable particles, and an overhead mixer with an angled four-blade impeller homogeneously mixed agar and fish residues. Overhead mixing also achieved a more homogenous sample than when hand mixing. A difference in firmness was also observed between agar made using induction cooking and the other methods.

Preparation of agar using induction heating created firmer agar than when using Quooker water. The three samples prepared to test agar mixing techniques using Quooker water showed lower firmness than the sample made using induction heating. In the induction heating process a change in viscosity could be observed. When the agar started to boil it became thicker. This was approximately 2 minutes after turning the induction cooktop on. All samples appeared similar, however, when finger pressure was applied, the sample prepared using induction cooking was almost impossible to indent. The other samples felt firm but exhibited elastic behaviour.

Methods examined for mixing agar and water yielded similar results and the agar concentration only had an impact when too low. Magnetic stirring, overhead mixing, and manual mixing using Quooker water yielded agar with a similar appearance and comparable consistency. Only a slight difference in firmness was observed between concentrations of 25 g/L and 50 g/L agar, whereas the sample prepared with 15 g/L was fragile. The 25 g/L sample was slightly softer to the touch than 50 g/L.

Of the impellers studied, the angled four-blade impeller created the most homogenous agar-fish residue mixture.

Number	***Description***	***Derived from topic***
1	The system must be able to process at least 10 kg of fish waste per hour.	Economic feasibility assessment literature
2	The system can be operated by a single operator.	Economic feasibility assessment literature
3	The contents of the product can be traced to the species level using DNA analysis.	Background
4	The product has a minimum shelf life of one week under refrigerated storage.	
5	The feed is palatable to dogs.	Evaluation of nutritional value for pets
6	The feed is safe for consumption by dogs.	Evaluation of nutritional value for pets

Table 10. Design requirements for an FRP-system on Bonaire.

The flat four-blade impeller and angled four-blade impeller created a well-defined vortex in water. The spiral impeller created turbulent flow in the beaker and had a poorly defined vortex. The spiral impeller was therefore excluded from agar-fish residue mixing. When mixing agar with fish residues using the flat blade impeller, they became entangled around the blades, no uniform mixture was achieved. The angled four-blade impeller did not have this issue and created a homogenous mixture.

When agar was manually combined with fish residues, a firm sample was produced that could not be indented by finger pressure, similar to when agar was cooked. Mixing was less uniform at the edges, which showed signs of crumbling. This had already been anticipated by the caretaker supervising the process. He mentioned that when the process was performed the first time achieving homogeneous mixing is hard. It takes practice to get the agar and residues to mix correctly.

Shaping feed particles

Dicing followed by electric shaving proved to be an effective method for producing water-stable feed particles of various sizes when agar was prepared using an induction cooking (Figure 27). Manual shaving yielded stable particles both with and without fish residues present. In contrast, extrusion did not produce well-shaped particles, and spherification was only successful for agar alone.

When manually shaving, only agar produced on a cooktop yielded firm shavings. Shavings produced from agar prepared using Quooker water and magnetic stirring were not stable. Similarly prepared agar that was mixed with fish residues also did not yield stable particles. Frozen samples could not be shaved, as they were too rigid to fragment. In contrast, all samples prepared using agar made on an induction cooktop and mixed using overhead mixing yielded stable shaving particles, both for agar-only and agar–fish residue mixtures.

Using a Dynacube followed by electric shaving yielded firm particles whose size could be varied. Electric shaving of agar prepared on an induction cooktop with the coarse grating drum created stable particles with good separation. The length of these particles was determined by the dimensions of the agar input. To create smaller input material, the Dynacube was used. When using an agar slab as input, firm particles were achieved but with varying sizes, with the length showing the greatest variation. It was observed that, when feeding in the material, it already sank into the blades of the dicer. When using a moulded agar block, the dicer did not cut into the material.

Figure 27. Feed particles produced by dicing (left) followed by coarse (middle) and fine shaving (right)

Dicing of the block with both the coarse and fine dicer yielded cubes with equal dimensions in all directions. Shaving the fine cubes with the coarse and fine drums on the vegetable cutter yielded fine and coarse shavings of approximately equal dimensions in all directions. Similarly, when an agar–fish residue mixture was used, stable particles of various sizes were formed.

Extrusion of agar did not yield a firm or well-shaped mass, either when agar alone or an agar–water mixture was extruded. Upon exiting the garlic press or potato ricer, the material separated into strings but adhered upon contact. When agar prepared on the induction cooktop was extruded, firmer particles were obtained, although they remained moist and required considerable pressure to extrude. Extrusion of an agar–fish residue mixture required even greater force and did not produce well-shaped or firm particles.

Spherification using agar prepared on the induction cooktop yielded well-separated and well-shaped spheres. When agar prepared using an electric kettle and manual stirring was used, spheres initially formed in the oil but quickly lost their shape. When the agar was prepared on the induction cooktop and a higher amount of oil that had been cooled was used, spheres with good stiffness were formed (Figure 28). The addition of fish residues increased mixture viscosity, limiting syringe uptake and preventing dropwise dispensing. Instead, the material formed continuous strings.

Buoyancy

Stable, buoyant agar shavings were produced by aerating agar prepared on an induction cooktop using an overhead mixer fitted with a whisking coil. Buoyancy was not achieved for an agar–fish residue mixture. Hand whisking also did not produce buoyant agar. Through using a handheld electric whisk buoyant agar was achieved, however, the material was insufficiently stiff.

In the first hand-whisked sample a negligible amount of air bubbles was trapped, in the second sample air was trapped but the sample did not solidify. The first sample was made in a plastic beaker the shallowness of the beaker prevented adequate whisk movement. When sectioning the sample only three air bubbles could be identified. The bowl used for the second sample allowed for sufficient whisk movement. Air got trapped in the agar and it showed a foam-like texture. This method was ineffective because the agar did not become firm in the fridge.

Using a handheld electric whisk, a buoyant sample was created. This agar was made by hand-stirring agar and Quooker water. When electrically whisked, air bubbles of around 1 mm were introduced into the agar. If the agar was whisked before it started to solidify, at low viscosity air bubbles were distributed throughout the agar and foam formed on the surface. When the whisking was stopped, the bubbles disappeared again. Conversely, when the agar was whisked as it started to solidify, at higher viscosity the air bubbles were retained in the agar. After solidification, air bubbles were visible throughout the sample. The trapped air achieved buoyancy of the sample. The sample was fragile around the edges and ruptured easily. The second agar sample was made using induction cooking to achieve a firmer agar. The whisk was unable to aerate the agar because of its higher viscosity compared to the other sample.

Figure 28. Water stable agar spheres.

Buoyant agar shavings were created using an overhead mixer by aerating it twice using a whisking coil. The overhead mixer could provide the torque needed to whisk the more viscous agar prepared on an induction cooktop. When aerating the agar once before it started to solidify air bubbles were trapped in the agar. A cube of this material was found to be buoyant. Subsequently coarse and fine shavings were tested, they were only semi-buoyant. A subsequent sample that was aerated twice produced buoyant fine and coarse shavings (Figure 29). It was observed that air bubbles could be trapped before the agar began to solidify, and a second aeration resulted in a higher density of air bubbles. Adding fish residues to agar samples aerated similarly did not yield solid samples. When the aerated agar was mixed with residues, the mixture did not solidify, and the air bubbles were no longer visible after mixing.

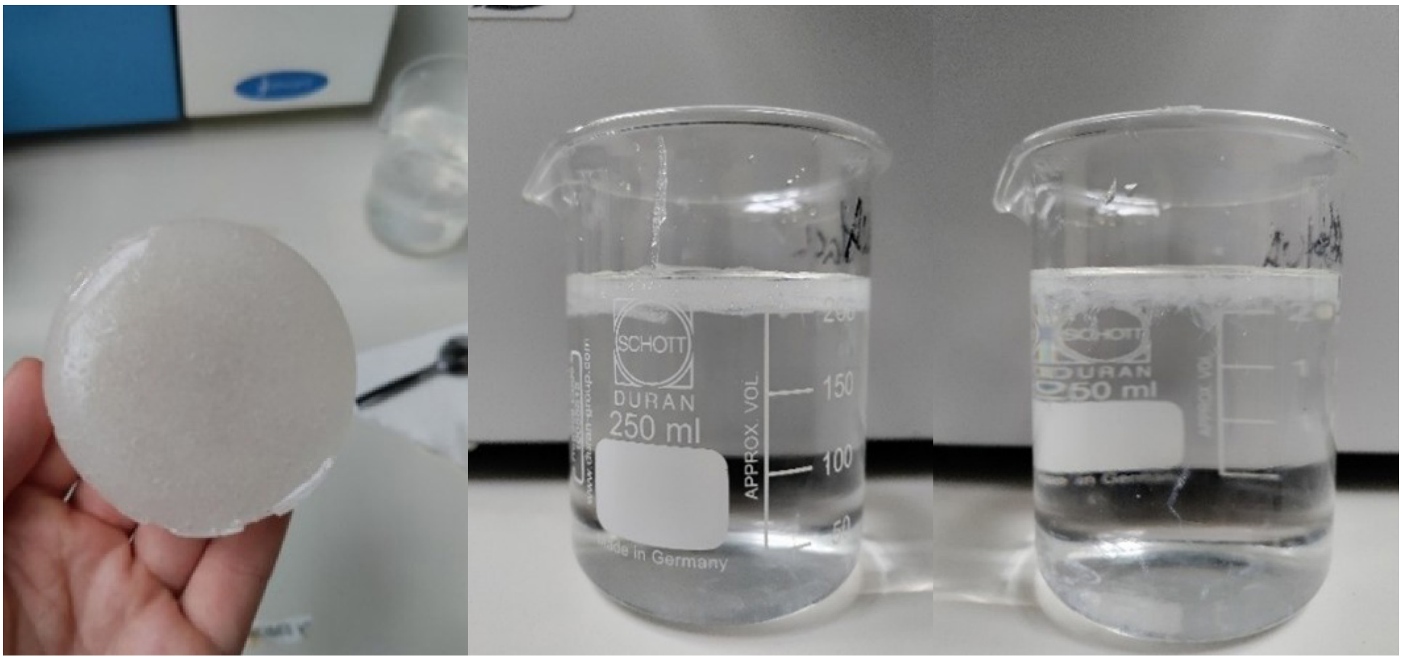


Figure 29. From left to right: air bubbles in solidified agar, floating coarse shavings and floating fine shavings.

Automated agar making

An automated cooling setup using an overhead mixer and a heating plate (Figure 30), was effective in automating the agar cooling process. This is a process which currently has to be monitored by a caretaker, as described in section Feed usage and waste materials. Full automation of boiling, cooling, and subsequent holding at the targeted 50 °C was not achieved. The full process took approximately 50 minutes, and during holding the temperature fluctuated around 50 °C with deviations of −5/+2 °C and −2/+5 °C.

Effective cooling and holding of agar at 50 °C (± 1.5 °C) (Figure 31) was achieved by setting the stirring plate at 51°C, a target temperature of 49 °C with an offset of 0.2 °C. This was combined with automated stirring for 15 seconds at an interval of one minute. Results of all the tests with cooling and holding can be found in Table 11. The water–agar sample was held at 50 °C for 1 hour and 30 minutes. At this point, solidification of the agar was observed at the edge of the agar where it touched the pot. Solidification started around the temperature probe.

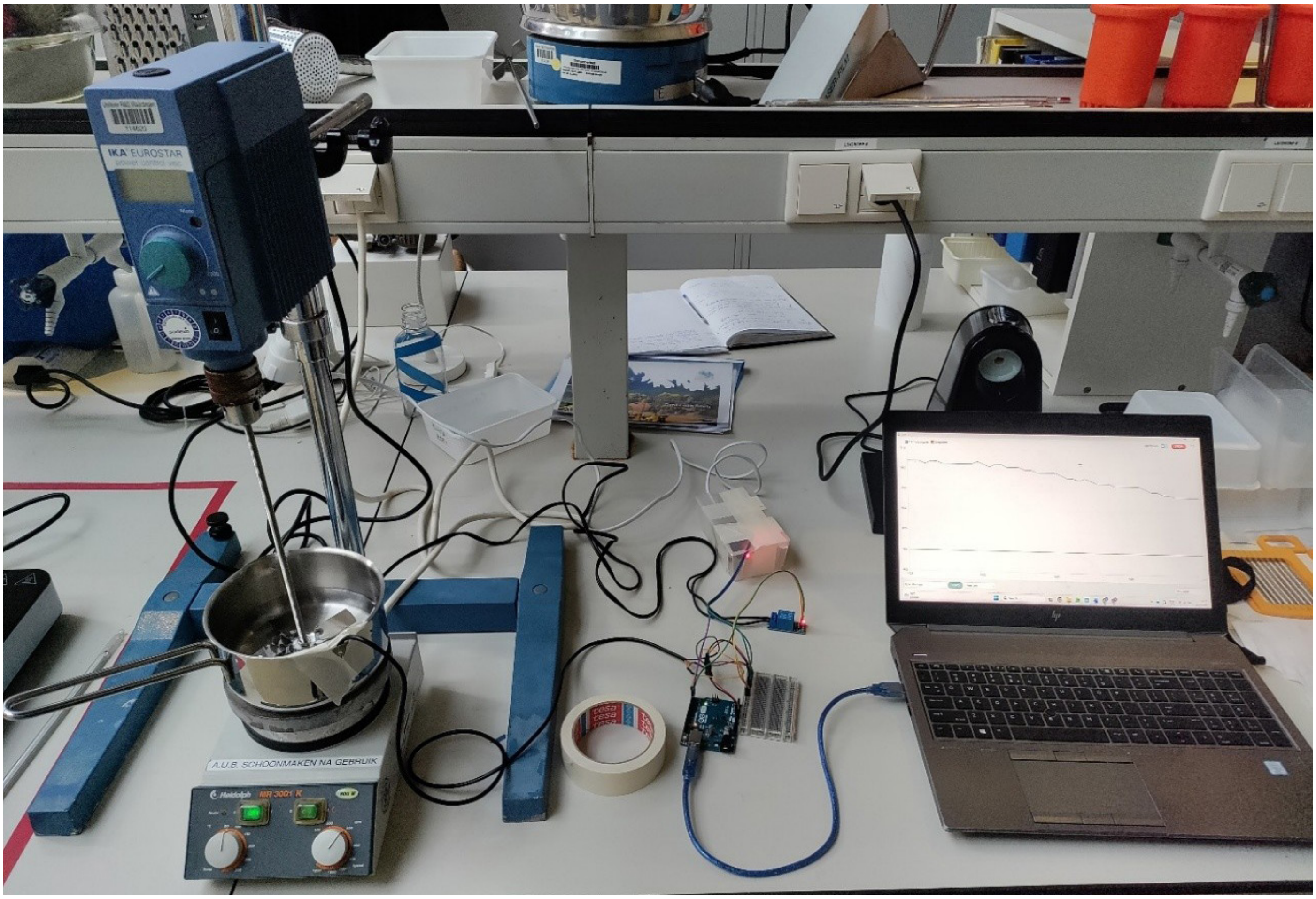


Figure 30. Automated agar cooling setup, using a heated stirring plate, overhead mixer and a microcontroller.

liquid type	Stirring type	Stirring plate temperature (°C)	Target temperature (°C)	Offset (°C)	Max Above 50 °C (°C)	Max below 50 °C (°C)
Water	Manual	125	50	2	4.8	1.2
Water	Manual	80	50	0.2	4.6	0.37
Water	Automated	51	49	0.2	3	2
Water + agar	Automated	51	49	0.2	1.5	1.5

Table 11. Temperature control performance of the automated cooling setup.

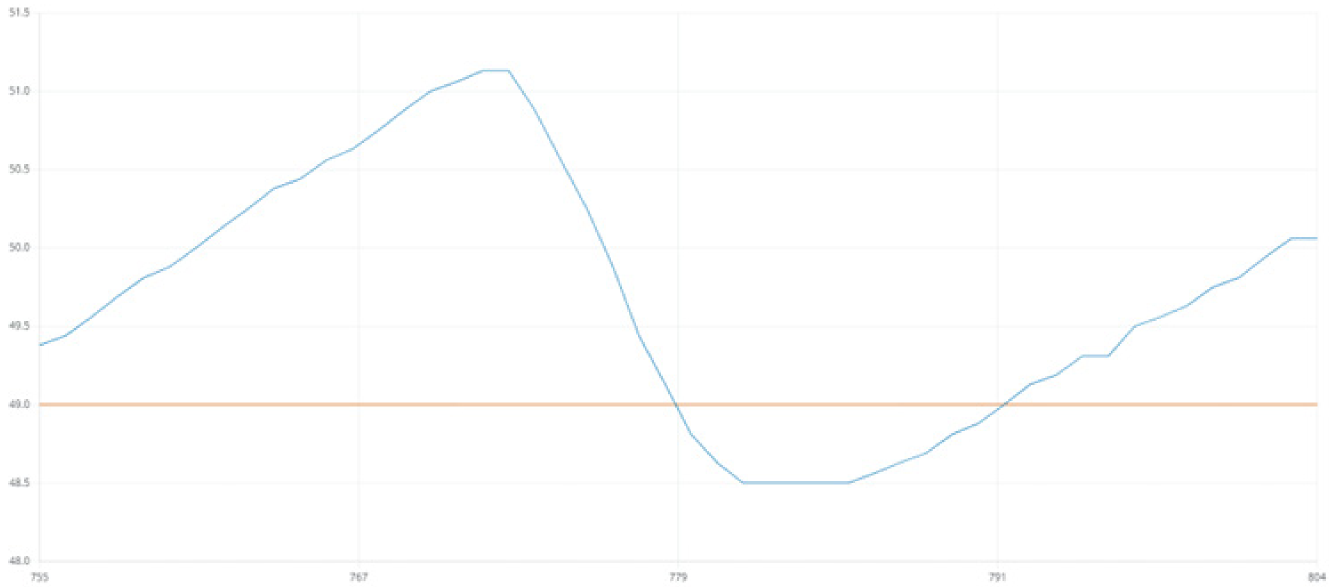


Figure 31. Temperature readings of the cooling setup effectively holding agar at approximately 50 °C.

FRP-system prototype Blijdorp

The feed from the prototype FRP-system could replace several dry feeds used at Blijdorp. A reduction of operator involvement was also achieved. Economic feasibility was not achieved with the current processing capacity. Buoyant feed could also not be produced using the prototype.

The system prototype consisted of an immersion blender, an induction cooktop, the automated agar cooling setup, a Dynacube and an electric vegetable cutter (Figure 32). The automated cooling setup consisted out of a heated plate and an overhead mixer equipped with an angled four-blade impller. Making agar using an Induction cooktop was found to be most effective to achieve rigid agar. The angled four-blade impeller was effective in mixing agar and fish residues. It was also suitable to intermittently mix during the agar cooling process. Dicing using the Dyancube followed by shaving on the vegetable cutter was found to be effective in producing various sizes of water stable feed. When using the system agar was first prepared on the induction cooktop. This was done by mixing agar and water by hand in a pot while heating. The pot was then placed in the automated cooling setup. Once the agar was cooled to 50 °C fish residues could be mixed in using the overhead mixer. The mixture was then poured into a mould and left in the fridge. The Dynacube and vegetable cutter could then be used to acquire the required sizes. An overview of the complete processing workflow is illustrated in Figure 33.

Figure 32. FRP-system prototype, from left to right: immersion blender, automated cooling setup, Dynacube, and vegetable cutter.

A walkthrough of the prototype system was conducted with an experienced caretaker. He considered the agar production method promising. He mentioned that this method was safer and less of a hassle compared to taking Quooker water and placing it in the microwave, as was currently done. He also expressed that automating the agar production would save time and reduce the risk of having to remake the agar due to excessive cooling. The idea of a further automated process in which cooking and cooling were integrated into one setup also appealed to him. He would have liked to see the temperature probe removed from the prototype, as it became contaminated with agar. The feed produced by the system was considered to be of good quality. Its consistency was the same as that of the feed they made themselves. He thought the various feed sizes produced helped in the applicability of the feed. He did remark that the smallest fish likely require a finer feed size than the prototype is currently able to produce.

Two out of the five dry feeds in use at Blijdorp could be replaced with the alternative made by the FRP-system, based on their dimension and water stability. The medium pellet could be replaced with the small shavings and the sticks with medium shavings (Table 12 and Table 13). The feed remained stable in water. The smallest particles produced with the system were immersed in water and remained well separated and retained their shape.

Using the system, operator involvement was reduced by approximately 15 minutes. However, the overall process still took about twice as long as required to be economically feasible. An overview of the time recorded for each process step can be found in Table 14.

Type	*Shape*	*Size (mm)*
Small	Shaving	3 x 3 x 3
Medium	Shaving	5 x 5 x 5
Large	Cube	8 x 8 x 8

Table 12. Feed particles sizes created by the prototype.

Type	*Size (mm)*
Flake	2 x 0.2
Small pellet	1 x 1
Stick	10 x 3
Medium pellet	3 x 3
Sturgeon pellet	9 x 12

Table 13. Dry feed types in use at Blijdorp and their dimensionautomated cooling setup.

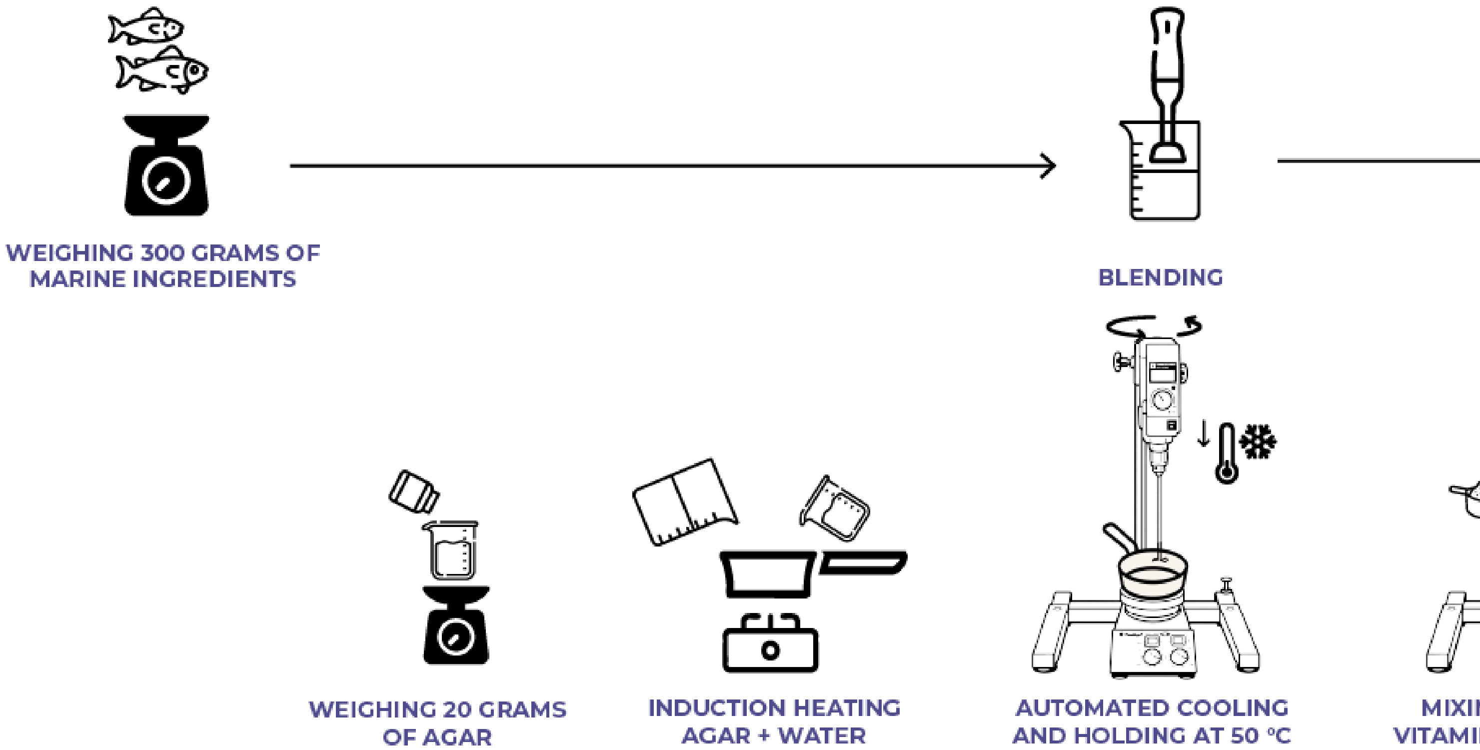
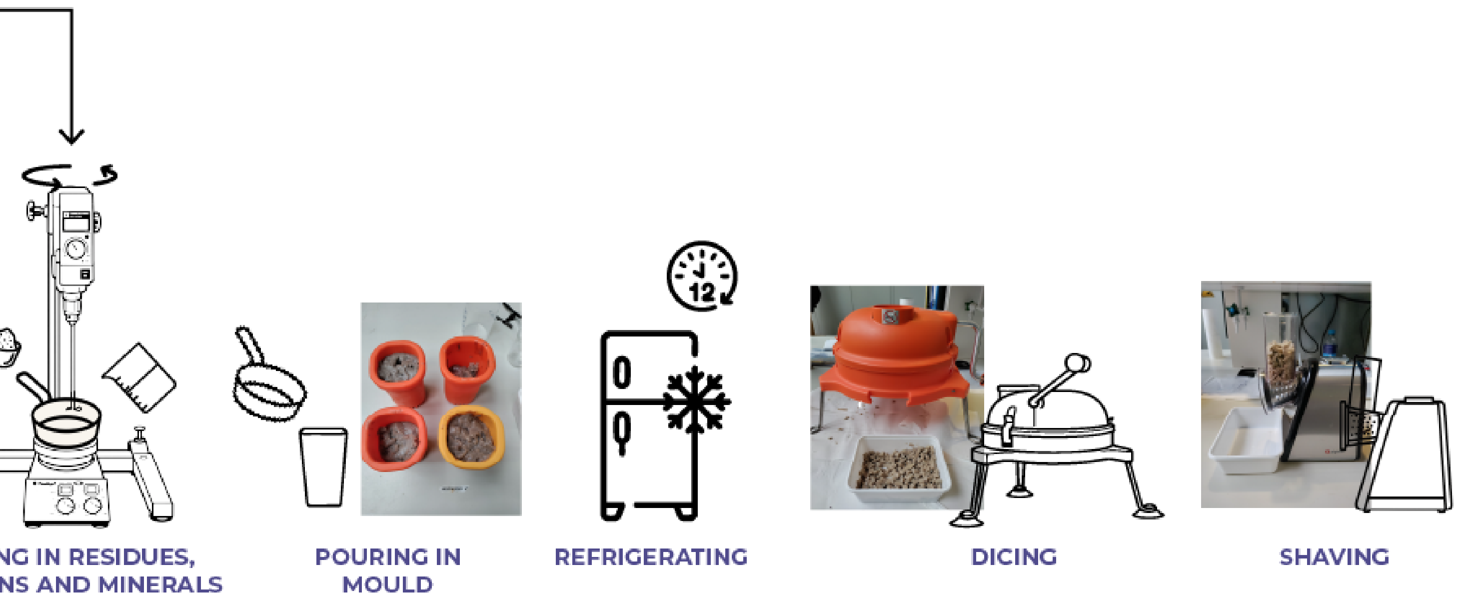


Figure 33. Graphical overview of the FRP-system processing steps.

The total time required to produce 720 g of feed (400 ml water, 300 g fish residues, and 20 g agar) was ~19 minutes.
This meant that 26 minutes were required to produce one kilogram of feed. This was around twice the time defined in the requirements (15 minutes) to make the process economically feasible. A reduction in operator involvement was achieved because the operator previously had to monitor the agar cooling process, which took approximately 15 minutes. With automated cooling, this was no longer necessary.

Process step	Time (min)
Weighing fish	2
Blending	3
Weighing agar	2
Induction heating	3
Mixing residues + pouring mould	4
Dicing and shaving	5
Total	*19*

Table 14. Recorded durations of processing steps performed with the prototype system.



Concept of FRP-system Bonaire

A concept of an FPR-system was designed that could process 10 kg of fish waste materials into dog food portions of 375 g. The cost price of this unit was estimated at $3400.

The main assembly of the concept consisted of a jacketed stainless-steel vessel with a cooling system, a steel frame, a 3500-watt induction cooktop and a mixing motor with an angled four blade impeller. Next to this a stainless-steel pot with a 500-watt blender was needed and a tray with a cutting tool. A render of the system can be found in Figure 34. To use the system the main vessel is filled with water and agar powder is added. This is then mixed while heated till boiling. After boiling the agar is cooled down to 50 °C and held at this temperature. During cooling the fish residues could be weighed and blended smooth. The agar and fish residues could then be mixed. Afterward the material could be poured into a tray. This tray was then placed in the refrigerator for the material to solidify. After solidifying the material could be sliced using the cutting tool. A full overview of the process can be found in Figure 35.

Stainless steel vessels were selected with a volume of 26 liters and a diameter of 32 cm for mixing and blending. This was a standard size. The total volume of all materials to be processed was around 24 kg or 24 liters (Table 15). This was calculated from the processing capacity requirement and the ratios used for waste recycling at Blijdorp. A 26-liter vessel was selected to leave some headroom. Stainless steel chosen for its durability, heat capacity and because it could be used on an induction cooktop. The induction cooktop was chosen for its efficient heating, its effectiveness in the Blijdorp prototype and because it could be electronically controlled. An induction cooktop (HENDI Inductiekookplaat Model 3500 D XL; HENDI B.V., De Klomp, Netherlands) of 3500 W was chosen because this was the most powerful heating plate that could be run from a standard 230-volt wall plug. More power was favourable to heat the mixture faster.

Material	Weight (kg)
Agar	0.7
Water	13
Fish rests	10
Total	24

Table 15. Materials and their associated weights based on the ratios used at Blijdorp.

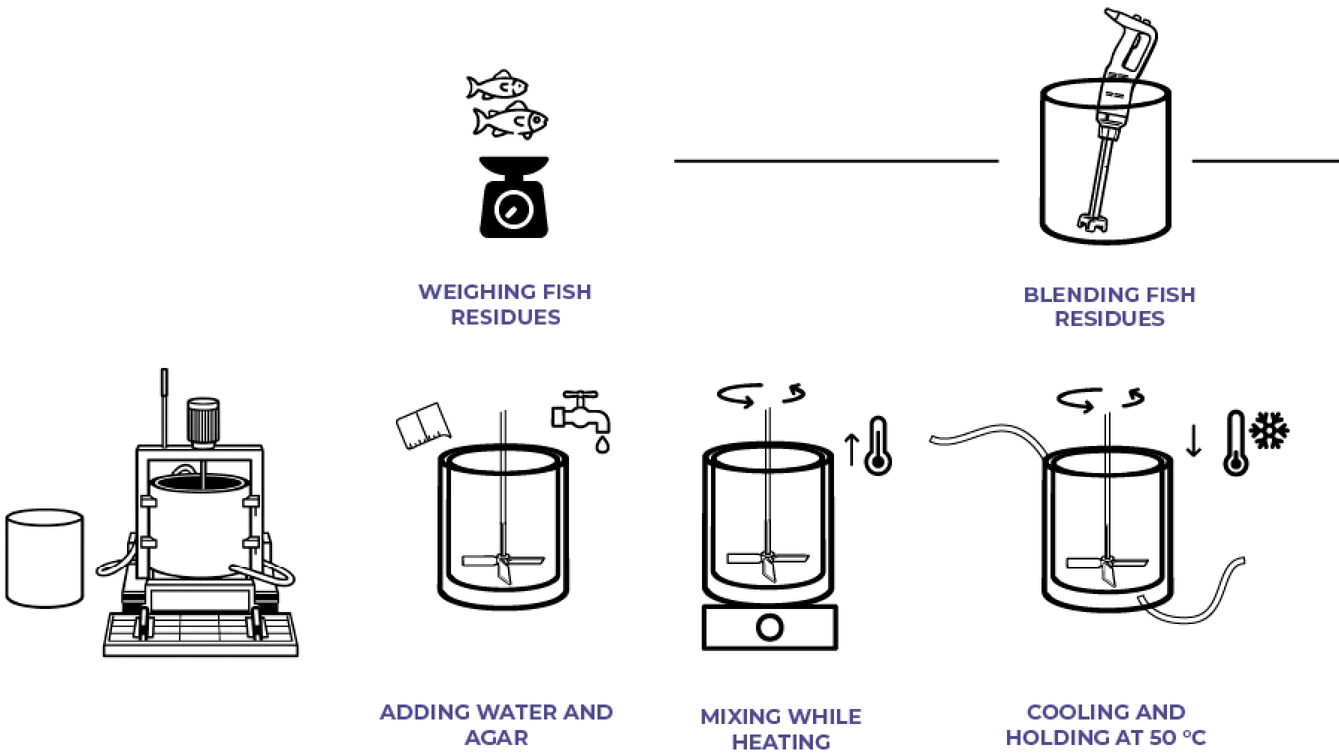
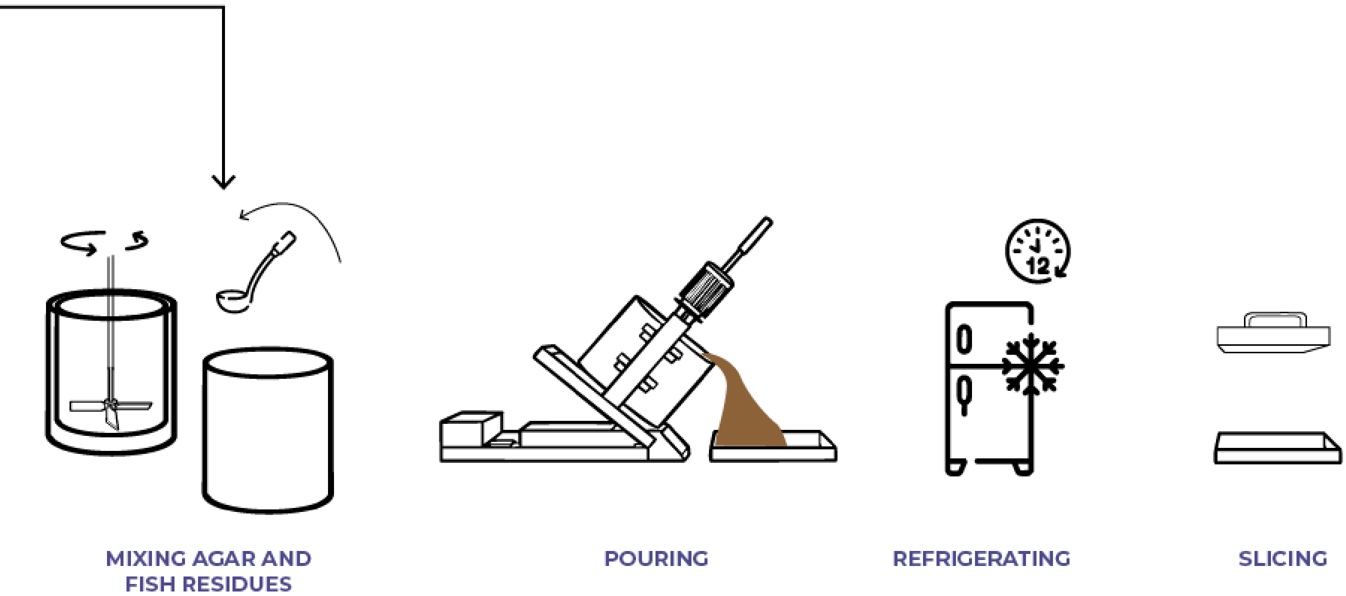


Figure 35. Graphical overview of the FRP-system concept processing steps.

Figure 34. Concept of FRP-system, showing on the left a stainless-steel pot with a blender, and on the right the main assembly with the cutting tool.



An industrial immersion blender was chosen to blend the fish residues, and an angled four blade impeller was chosen for mixing. An immersion blender (HENDI Staafmixer 500; HENDI B.V., De Klomp, Netherlands) of 500 watt was chosen. The blender could blend fluid capacities up to 120 liters and should be more than sufficient to blend the 10 kg of fish rest materials. The angled four blade impeller was chosen because it provides both axial flow and radial flow, leading to good overall circulation. An anchor or helical impeller was also considered as they are effective for high viscosity materials. These were not chosen because fish residues could get tangled in the helical impeller and the anchor impeller does provide good heat transfer but does not offer good mixing. The impeller could be purchased in combination with a suitable motor equipped with speed control. Speed control was chosen because it was likely that for making the agar and mixing the agar and fish residues different speeds were needed.

A jacketed design was chosen for the cooling system (Figure 36). Using a jacketed design, the system is expected to both heat and cool the mixture effectively. By placing the mixing vessel of 26 liters in a bigger vessel a jacket is created. The bottoms of the two vessels are attached flat to each other. This way the mixture can still be heated from below. An inlet hose can be placed at the top of the jacket and an outlet hose at the bottom at the opposite end. The inlet can be connected to the tap water system to create water flow in the cooling system. Additionally, a pressure reduction valve and solenoid valve could be connected to the inlet hose. This way the water pressure could be tuned to create the correct water flow. Using a solenoid valve the water flow could be turned on and off electronically. This combined with electronically controlling the induction cooktop formed a hysteresis control system. When the temperature was above 50 °C the solenoid was open and the heating was off. When the temperature dropped below 50 °C the solenoid was closed and the heating was turned on.

A frame was designed from steel box section to enable pouring. The frame enabled the tilting of the vessel to pour the mixture onto a tray, as visualized in Figure 37. The vessel could be tilted forward to a maximum of 90°. This motion was enabled by hinges at the front of the frame. At the back of the frame a counterweight was placed to counter the momentum created from tilting the vessel

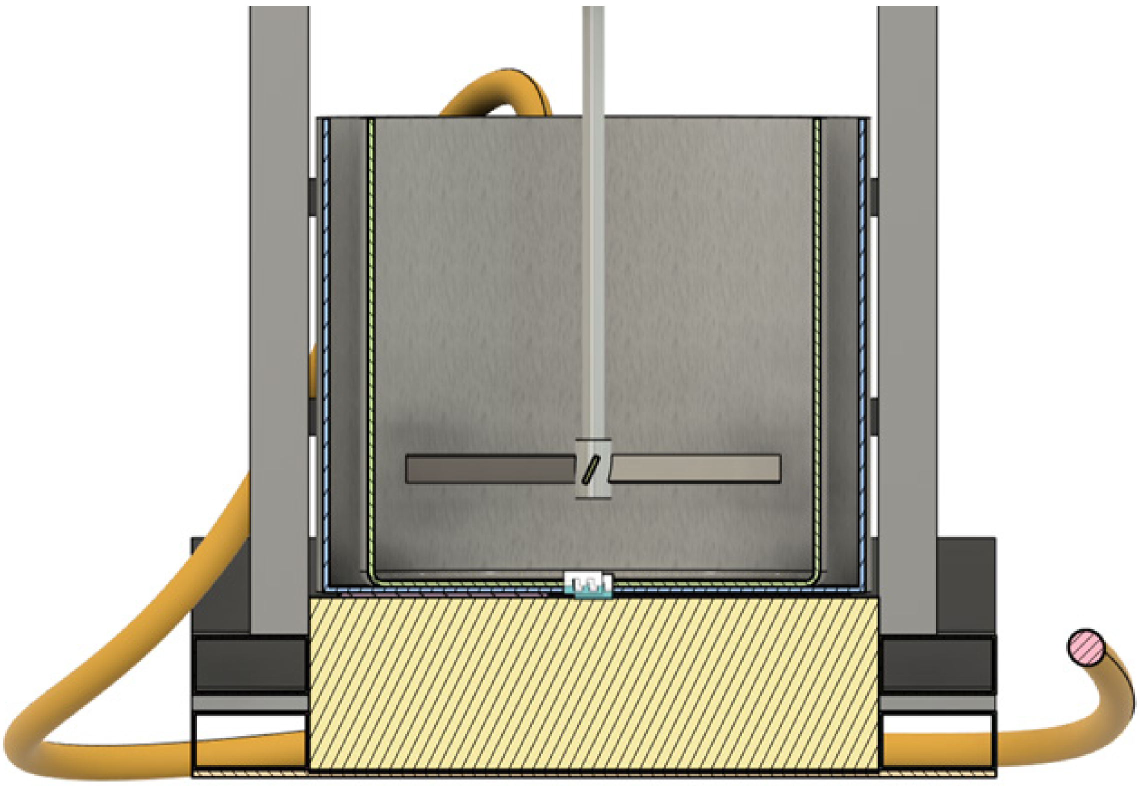


Figure 36. Cross section of the main assembly where the jacketed vessel is visible.

forward. A handle was added to the frame to make it easier to tilt it forward. L-shaped brackets were used on either side of the frame to ensure the full weight of the system did not rest on the induction cooktop. When tilting started the brackets would slot into cavities attached to the pot, as can be seen in Figure 38. This resulted in the pot being lifted off the induction cooktop. A tray was chosen to pour the material onto. The large surface area would aid in cooling down the material. After letting the material solidify, a grid cutting tool could be used to cut the material into the required servings. For the serving size, it was assumed that the product would be sold as wet dog food. The standard serving size for wet dog food on Bonaire was 375 g. The associated serving size then was 125 x 75 x 40 mm, assuming the density of the material was similar to water. A grid cutter was designed that could cut the material into 25 servings in one go. Out of the full batch 64 servings could then be obtained.

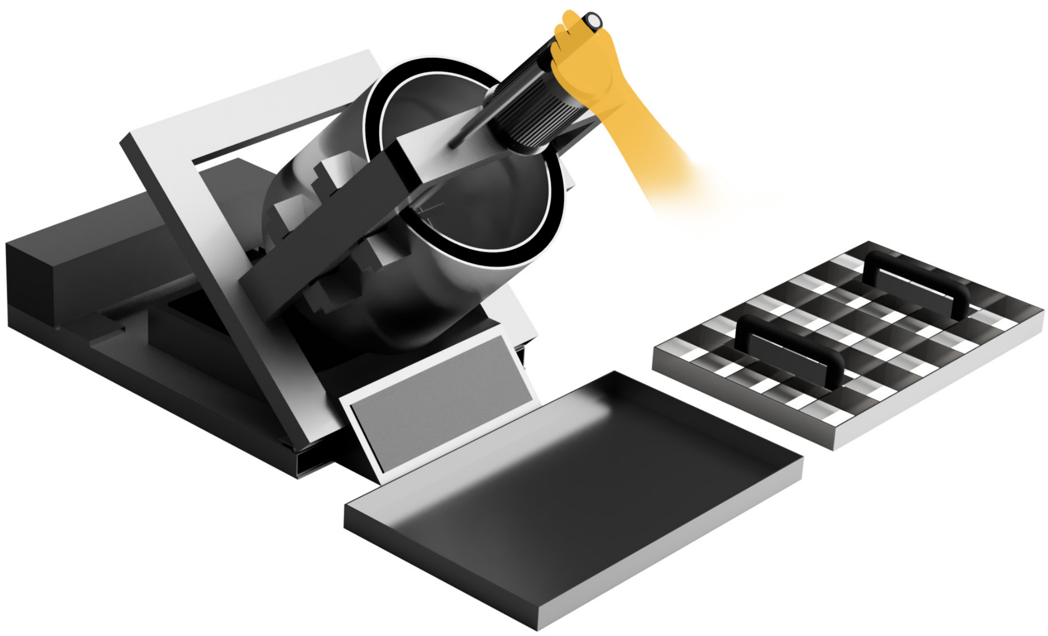


Figure 37. Render of the vessel tilted forward to enable pouring of the mixture into the tray.

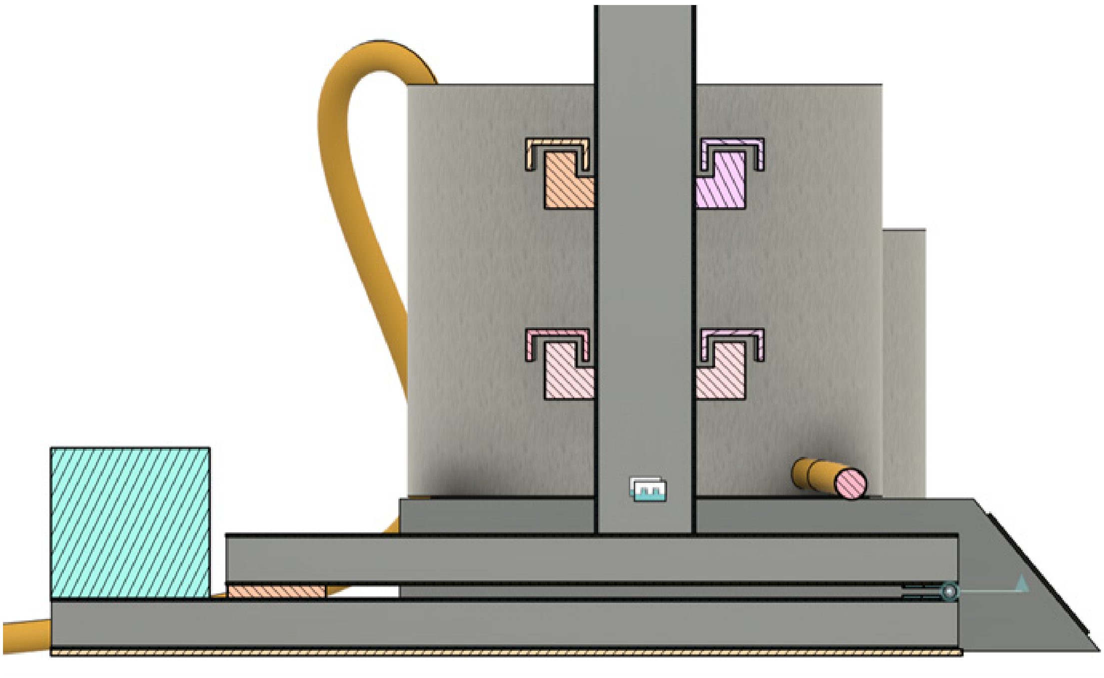


Figure 38. Cross-section of the main assembly, showing the counterweight at the rear (blue) and the L-shaped brackets (pink and orange).

The cost price of the system was estimated at around €2900 or $3400. The full cost price breakdown can be found in Table 16. Most components could be bought off the shelf except for the frame. A conservative estimation was made on the cost price of constructing the frame. Added to this price estimate were other parts that needed to be fabricated. This included the lifting brackets and the assembly of the pots to form the jacket. This total estimated system price was slightly higher than the estimation of $3000 used in the section Economic feasibility assessment.

Type	Name	Retailer	Price (€)
Induction cooktop	Induction cooktop, model 3500 DXL	Hendi	265
Immersion blender	Immersion Blender 500	Hendi	193.85
Mixing setup (including pot)	Thickened Food Mixer	Zhengzhou Hanchuang Machinery Co., Ltd	259.55
Temperature probe	PT4 6 X150	Labfacility	68.5
Outershell	Saucepan, high, 47.2 L	Vogue	109.37
Metal box section	Box section 80x40x2mm	Ijzershop	66
Hoses	25-meter garen hose 1/2"	Ecotools	24.12
Tray	Tray siliconized 60x40x5cm	Baktotaal	82.2
Reduction valve	Honeywell pressure-reduction valve	Warmteservice	81.40
Solenoid	Magnetic valve, stainless steel, ½", normally closed, EPDM, 0–16 bar, 230 V AC	Tameson	44.62
Microcontroller	Arduino Uno	Elektronicavoorjou	24.95
Handle	Solid stainless-steel rod, Ø 20 mm	Ijzershop	14.81
Slicing blade			150
Blending pot	Cooking pot, 26 L, 32 × 32 cm, stainless steel (32 × 32 cm)	huismerken.nl	79.99
Hinges	Pinet Steel Butt Hinge, 80mm x 80mm x 2.5mm	RS components	22.24
Couplings			40
Relay (2x)	Relay module, 1 channel, 5 V	Hobby elektronica	3.5
Bottom plate	Steel plate, 500 × 1000 × 5.0 mm	Ijzershop	62.17
Counterweight	Ballast lead blocks, 40 kg	Ballast producten	112
Frame assembly + custom part production			1500
		Total	2929.02

Table 16. System components with their associated manufacturers and costs.

DISCUSSION

DISCUSSION

Research Aim

The aim of this research was to investigate, and develop, a system to transform fish rest materials into traceable aquaculture and pet feeds to support sustainable fisheries. Designing of this “Fish Rest Processing system” (FRP-system) was split in two steps. The first was at the Oceanium of Blijdorp, where fish rest material of known origin could be used to replace dry aquaculture feeds. The aim of the second step was to adapt the FRP-system to one of producing pet feeds out of fish rest material on Bonaire, while ensuring traceability.

Main results

For both Blijdorp and Bonaire, FRP-system requirements were defined. For Blijdorp, a prototype FRP-system was designed in which feed was produced by binding agar to fish residues. In this process, the fish material was not exposed to temperatures above 50 °C, which should limit nutrient loss and support traceability. The system was capable of producing feed in various sizes that remained stable in water. In addition, a conceptual FRP-system was designed for Bonaire that could process 10 kg of fish residues per hour into 375 g portions of dog food. This design was based on the underlying processes developed for the Blijdorp prototype. The core process for both systems consisted of cooking agar using induction, followed by automatic cooling of the agar to 50 °C. This temperature was then maintained using hysteresis control. The fish residues were then mechanically mixed using an angled four-blade impeller. Finally, the material was poured into a mould that could be placed in a refrigerator, after which it was processed into the desired final size. Grating and cutting with a Dynacube proved to be effective methods for obtaining different aquaculture feed sizes. For Bonaire, a dedicated cutting tool was designed to produce standardized portions of dog food.

Interpretation of Results

The results indicate that it is possible to produce traceable fish feed from fish waste materials. Currently, it can be difficult to trace the original fish species used in aquaculture or pet food, mainly because DNA degrades during thermal processing. In the developed prototype, the fish residues were not exposed to temperatures above 50 °C, which is expected to make it easier to trace the original species. This was also the temperature maintained by Blijdorp to prevent nutrient loss.
The findings imply that several types of conventional aquaculture feed currently used at Blijdorp could be replaced with a traceable alternative. The produced feed was stable in water, which is essential to prevent nutrients from dissolving. It was also possible to produce two feed sizes that correspond to the sizes of aquaculture feed currently in use. Feed size was an important indicator, as specific feed sizes correspond to consumption by fish of specific sizes.
The findings further show that producing traceable pet food on Bonaire is possible. Since the same underlying processes were applied in both the prototype and the conceptual system, this pet food should also be traceable. On Bonaire, larger quantities of waste material are available. To make effective use of this, the system was designed for a production capacity of 10 kg per hour. This capacity was based on the maximum required capacity identified through a literature study. It was also found that selling the product generated by the system would be most profitable if sold as wet dog food. The system produced portions of 375 g, which was the standard weight on Bonaire.

Implications

Where fish waste products are available, opportunities exist. An underlying system has been developed that can process waste materials into both aquaculture feed and pet food using mechanical processes. This system could be adapted for parties that generate fish waste. A clear opportunity exists for zoos such as Blijdorp, where fish residues remain after feeding animals. The system could also be further developed for fishmongers or other parties that produce fish waste on a large scale.

At Blijdorp, only 215 g of dry aquaculture feed is used, but part of this consists of fishmeal or fish oil. Replacing this feed only eliminates a small fraction of feed with low traceability. The size of the produced feed is currently limited by the grater size in the vegetable cutter and the cutter in the Dynacube. By adjusting these components, several other aquaculture feed sizes could be produced. In addition, the first steps have been taken toward producing floating feed. Together, these developments could lead to the replacement of a much larger share of aquaculture feed.

Limitations

The prototype and conceptual FRP-system were developed based on recycling waste materials as currently practiced at Blijdorp. This involved binding agar to fish residues without exposing the material to a temperature above 50 °C. No research was conducted into alternative processes that might also be capable of processing the material into feed at low temperatures. Furthermore, it has not yet been investigated whether adequate nutritional value can be achieved with this process. The same applies to shelf life, which has not been investigated.

When selecting components for the prototype, equipment already available at Blijdorp was primarily used, mainly due to budget constraints. Some inexpensive devices, such as a vegetable cutter, could be purchased. As a result, components offering better performance may have been overlooked. The same applies to the conceptual system, due to limited time, components used in the prototype were scaled up. It is possible that better options exist for upscaling.

For this study, it was decided to first establish design requirements for both systems. For Blijdorp, this involved extensive on-site research combined with a literature review. For Bonaire, information was difficult to obtain due to the limited number of publications. Both of these led to significant time investment in defining requirements. Consequently, limited time remained for developing the prototype and conceptual system. A less theoretical and more exploratory approach may have been more appropriate, given the uncertainties surrounding the requirements. Such an approach could have identified a wider range of possible system components.

Recommendations

The prototype built at Blijdorp should be further developed into a system capable of reliably producing feed. At present, the system has only been used a limited number of times by someone familiar with its operation. For implementation, further testing should be conducted and improvements made where necessary. Caretakers should also be involved in further development. In collaboration with them, feeding the product from the system to the fish can be tested.

An on-site survey into fish waste on Bonaire, interviewing fish mongers and fishermen is recommended. There is limited literature available on fisheries on Bonaire, making it difficult to estimate how much fish is caught and, consequently, how much waste material is available. This information is crucial, as it determines the required production capacity of the system. Once this is known, components can be selected more effectively. With revised requirements, a prototype could then be designed and built for Bonaire.

The shelf life and nutritional value of the product must be determined. This study primarily focused on the technical aspects of a recycling system, but it is also essential that the nutritional value of the product is comparable to the dietary needs of the animals. Feed analysis should therefore be conducted. In addition, adequate shelf life is essential to sell the food. Food experts should be involved to assess this aspect.

Conclusion

In this study, the basic concept of binding agar to fish residues was developed into a laboratory setup capable of producing traceable aquaculture feed. From this, an underlying process was distilled, forming the basis for a conceptual system intended for larger-scale production. If the technical aspects are further developed alongside research into nutrition and shelf life, the production of traceable pet food and aquaculture feed becomes feasible.

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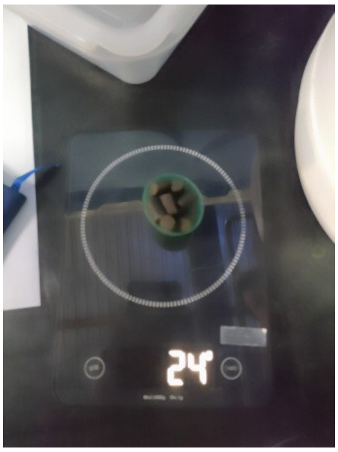
APPENDICES

APPENDICES

Appendix A – Feeding routine observations

Caretaker 1

In the morning it is decided who does the morning round. It is also discussed who is going to do what, together with the entire cold-blooded team, so these are fish + reptiles. During the dry feeding we first went to the North Sea area; here mainly the sturgeons received large pellets, and these pellets are brought to the bottom of the tank with a small net.



On the coral island, in the tank on the right, about 2.5 handfuls of small red pellets are administered. He indicates that he often mixes the brown and red pellets. Also, in the back right another half handful is fed. In the tank on the left, 1 handful is fed. According to the scale, a handful of the fine pellets weighs about 12 grams, however the empty container also seems to be 12 grams, so this may be incorrect. Flakes (red) are also fed here. For all animals it is checked whether they eat the feed. You feed as much as can be eaten by the animals in a short time. You feed until they do not necessarily want more. It is okey if they stay a little hungry. Because of this, it also varies a lot per day how much is eaten. Seaweed flakes are also fed here.

After this we walked to the area where animals are kept that are not accessible to the public. Fish are kept here that are housed at Blijdorp for preservation. A different type of feed is used here, a kind of stick-shaped feed. The scale acted a bit strange, but about 4 grams of the sticks were fed. A very fine pellet was also fed here. This feed is for the very smallest guppies that cannot eat anything larger yet.

Here a type of mix with insects is also fed, which was new to the care taker as well. We briefly talked about the fact that flakes are nice because you can make them as small as you want. A few remarks were also made that freshwater and saltwater fish have different needs when it comes to feed. It was also mentioned that the freshwater flakes are the colored ones. An interesting detail is that if people take the dry feed with wet hands it can start to clump.

After this we also fed downstairs in the tropical area. He indicated that in the tank where the doctor fish are now a lot is fed. In the aquarium below this another handful of sticks was given.

Back in the kitchen we talked with another care taker about making gel food. Making the gel food currently takes quite a lot of time. They both do not really enjoy doing it now, it feels like something you just have to do at the end of the day. One of them says that it takes quite a lot of time while he would rather spend that time on hygiene. The other also says that he finds it strange that this is the only food that is used the next day while the rest is thrown away. He also mentions that you are now basically mixing with water, which could affect certain nutrients.

During the wet feeding it appears that if a fish does not eat, it is taken out of the water again immediately to prevent rotting. The fish is offered to the other fish with a kind of grabber so the correct fish can be fed and there is a check whether it has eaten.

As far as I understand, ammonia and nitrate can be produced by feeding too much. I am not entirely sure anymore whether that is because the fish excrete it again or because it remains on the bottom

The animals are partly fed plankton. The smallest form of this fed is alternately cyclops and red plankton. The slightly larger one is alternately mysis and krill. Plankton basically describes all animals that cannot swim against the current by themselves. The largest of these is the jellyfish.

When feeding the cow-nose rays, a rotten fish is taken out of the water.
After this the gel food was fed. The lookdown fish mainly eat the gel food, the rays do not. We briefly talked about the consistency. Sometimes the gel food floats at the surface and sometimes it sinks to the bottom. This is still random.

We also briefly talked about the size. He sometimes intentionally makes larger blocks so that the snappers take them. Sometimes the blocks fall apart easily, or in other words they start to flake a bit. He finds this useful because the plankton eaters can also consume it.

Caretaker 2

Overall: this care taker had many question marks about what I was doing and wondered what it was worth it.

First we went to the coral island. Interestingly, he mixed some water with the different ingredients here. In the bucket with water he put sticks, pellets, and flakes. He did this so he could feed more easily. He did not really look for long to see whether the fish had eaten.

It was not completely clear to me whether the mixing was done differently per tank.
All the tanks at the coral area contain saltwater fish. You can recognize this by the fact that there is little vegetation in the tanks. In the freshwater tanks behind the scenes the guppies are fed very finely ground feed. On the tanks it is written whether they contain freshwater or saltwater fish. For some herbivorous fish a leaf with algae is placed in the aquarium.

The caretaker indicates that he thinks there is a difference in what should be fed to freshwater versus saltwater fish. He thinks it is better to feed freshwater fish to freshwater fish and saltwater fish to saltwater fish.

In all conversations with the care taker he seemed to find it a bit difficult to move away from the dry feed. He thought that the composition of this feed is perfectly made by the formulators. On the buckets it partly states what is in it.

At the quarantine area the caretaker mentions that the animals are there because they have just arrived or because they are sick. This does not apply to all animals because they simply have too little space, so other animals are also kept there. For the quarantine animals flakes are fed. He feeds quite a lot of flakes because the fish are fairly large and they still need to grow.

After this we briefly looked at the cupboard with dry feed. I saw that for different types of feed it does say roughly what is in it. Maybe it is an idea to categorize the feed for freshwater and saltwater fish?

Then we walked over to the cow-nose rays and the tank next to them. Here he states that he is not really a fan of the reused shark food. He says that he sees it as old feed, something he would not easily give to his own fish. I asked further about this because fishmeal is already older and dried. He says that because of that it would stay good. In short, he finds it important that the quality of the feed is good. I think myself that this is mostly a perception issue.

He also mentioned that fish do not have a feeling of satiety, which is an interesting fact to know. pointed out to him whether the sturgeons should have been fed. He says that we probably skipped this.

In two other tanks, the ones with piranhas and the other one, about six spirulina tablets are given. This is for the herbivorous fish that eat this from the bottom.

In the tank with the long-nose fish two handfuls of small pellets are given. This sinks to the bottom slowly, where the fish can easily eat it.

Nine people work at Blijdorp in the part that deals with feeding the fish.

Caretaker 3

We started the round again at the coral island. At the tank with the boxfish and the red batfish the seaweed leaves are put in. He places the one for the boxfish in its basket so it can eat calmly by itself.

The seaweed also goes into the tank on the right with the fish with the yellow backs, about two to three sheets. The tank in the back right where the nosefish are is called the naso tank.

The care taker mixes some of the red pellets with the green pellets, flakes, and spirulina flakes. He mixes this with the lid on the container and then spreads it out. He says that he does this with the current, so at the place where the water is pumped into the tank and not at the overflow, because that would pollute the system.

Here it was mentioned that the red flakes are mainly used for saltwater. The coral island is all saltwater.

After this we walked to the North Sea area. The mullets are in the tank on the right, with the sturgeons in the back left. They receive spirulina flakes. It is a Thursday, so the sturgeons do not get sturgeon pellets on this day.

The small tanks on the coral island are fed in a different feeding round called “block 1.” In the freshwater holding area on the right with the stacked tanks both animal-based and plant-based feed is given. The tropical flakes are used here, and also the spirulina flakes. The care taker mentions that the spirulina flakes are fed more to the animals that are herbivorous.

In the deep tank the sticks are given. He thinks we feed that here because of the compactness of this feed and because it falls apart less easily. Some of the fish here also receive frozen food in the afternoon.

The tank with the tiny fish in the back again receives very fine feed from the jar. The red pellets that are kept here are in principle not intended for the freshwater fish.

After this we walked downstairs with the take-along basket.

In the tank next to the outdoor penguins some spirulina flakes are given.
The tank with the fish with the yellow backs is also called the moray eel tank. The moray eels do not eat dry feed, they only eat the frozen feed. They hide between the rocks and usually come out to grab prey.

In the publab, which I guess is the public lab, they hardly use any dry feed because the corals there do not eat it.

The doctor fish, which are clearly also grazers, receive spirulina flakes and seaweed.
The care taker also always gives seaweed to the angelfish that is in the tank with the cow-nose rays.

The cichlids in the pike tank receive a handful of sticks. The catfish that swims lower at the bottom gets a few spirulina tablets, about two or three.

We had quite a long conversation about the mouth shape of fish. You can really see that bottom-dwelling fish have a mouth that is directed downward. You also have fish with a mouth that faces forward and fish with a mouth that points slightly upward. In the sturgeon tank you could clearly see that the different animals with different mouth shapes also swim in different parts of the water column.

In the tank next to the pike tank two handfuls of sticks are given. Two spirulina tablets are also put in here. One handful is put in the back to distract one fish species, and then a handful is put in the front for the catfish that likes to graze there.

In the Madagascar tank both sticks and flakes are given. The care taker says that some fish eat quickly and others more slowly.

In the piranha tank there are also some guppies as feed for the large striped fish because these do not want to eat dry feed.I did not see the insect flakes being used.

I also filled a container with dry feed up to about the level that the caretaker had for the round upstairs and then topped it up with what is fed throughout the day. Of course this feed is loose because it sinks.

I weighed this container and it weighs 0.215 kg, or 215 grams.

Appendix B – Observations fish kitchen and shark feeding

Meal preparation in the fish kitchen

The food that is prepared in the fish kitchen in the morning is alll the material that is used throughout the day

There is a cart with all kinds of fish already in the thawing room, which was taken out of the freezer the day before. In between we talked about what the "publab" is; this is the food for the anemones. Anemones are therefore carnivores.

You let the plankton drain so that the liquid runs out. Using the recipe book, all the food for the fish is prepared. First, the food that needs to go with the first feeding round is made. Today, for example, a feeding round takes place in the morning and the sharks are only fed in the afternoon. The shark food is therefore also prepared second.

Part of the food that is fed consists of whole fish. These are cut into bite-size pieces; sometimes the recipe specifies how large the pieces should be for feeding. Sometimes a fillet also needs to be fed; this means that the entrails and bones must be removed, and the fish is cleaned in a specific way. The remaining pieces, such as the heads, are kept and can be fed to the sharks on shark-feeding days. For each species the amount that is needed is weighed using a scale.

The lobster was not yet fully thawed, so it is placed in a container with water to speed up the process. This lobster comes from leftover products from cruise ships. By thawing faster with water, you probably lose vitamins because they dissolve in water.

The areas behind the scenes are called freshwater holding and quarantine.
The stingray that is here is being bitten by male stingrays and is therefore kept here in quarantine. This one, for example, does not need filleted herring because it can also eat larger pieces of herring.

For plankton types, from smallest to largest: cyclops, then artemia, and then mysis. This is when it is brown feed day; otherwise, the smallest plankton is used and the other one is krill.

The moray eels are in the tank with the fish with yellow backs at Coral Island. Coral Tunnel, I think, is the tunnel you can walk underneath. The coral tank is a kind of experimental area where children can sit close to the glass.

The nurse sharks are a kind of garbage-bin sharks; if there are heads or other parts left over in the morning, these go to the nurse sharks.

Some sharks that have issues or that do not want to eat are given a special diet. There is currently a nurse shark that is getting a different diet. The nurse sharks are the larger reddish sharks that lie on the bottom.

At the end, there are often different kinds of fish left over, which can be used to make re-used shark food. To make this, you put as many different types of fish as possible in equal amounts into a container. The total weight is 300 grams. There does not seem to be a fixed recipe for which fish goes into this.

When asked why they sometimes do not use the leftover products from shark feeding, the answer is that in the afternoon there are already many other things that need to be done, such as weighing back and cleaning, so you do not want to start collecting the ingredients at that time.

Some leftover products of which there is a lot are also given to the mammal caretakers so they can feed these.

In between, someone returns from their feeding round; whatever is left over goes back into the cold storage. This can be used again during later feeding rounds. After this, we started working on thawing; in principle, you thaw the food for the next day before 13:00. Some products, such as squid, need to be thawed earlier, two days in advance, because they contain so much water that otherwise they remain a block of ice.

In the freezer there is a cart with all the frozen products you basically need; you roll this to the kitchen, and whatever is missing on the cart is replenished in whole boxes. From this cart, the different types are taken, weighed, and placed in closed containers (preference-dependent) on another cart, which then goes into the cold storage so the products can thaw there.

Fish parts that fall on the floor or are contaminated in any other way go directly into the waste bin.

Shark feeding

During shark feeding, a lot of leftovers can remain. The sharks are fed using long sticks where the food can be squeezed in between, once the food is in the tank, you can release it. The sharks are fed for about 15 minutes.

The cart with leftover product from the shark feeding is then taken back to the fish kitchen. In the fish kitchen, the fish is weighed to document how much the sharks have eaten. If very little is left, it is not weighed and it goes directly into the waste bin.

Everything that remains is collected in one container, which is then placed back in the refrigerator. It is placed in the mammal section of the refrigerator. The mammal caretakers can then decide whether they want to feed the leftovers. They don’t really like items that have been cut. Sometimes, leftovers are also placed in a yellow container for the polar bears with a layer of water, creating a type of ice treat.

Today, there was quite a large container of fish left after the shark feeding. When asked whether this is processed into reused shark feed, the caretaker said that he had already used the leftover product from the morning cutting to prepare a reused shark food container. He placed this container in the refrigerator upstairs.

When asked why leftovers remain when taking food out, the answer was not very clear, but the mammal keepers sometimes take whole fish, which can leave leftovers, especially because they do not have precise scales.

Appendix C – Waste stream quantification

Example of a filled in overview for a specific week. The amount eaten (gegeten) was filled in and the total that had been fed (total). The total waste material per day was then calculated using this. Additions of the days results in a weekly total. Similarly the total per species over the week is calculated.

Weeknummer:		52	Jaar:	2024											
	Maandag		Dinsdag		Woensdag		Donderdag		Vrijdag		Zaterdag		Zondag		
Vissoort	Gegeten	Totaal	Gegeten	Totaal	Gegeten	Totaal	Gegeten	Totaal	Gegeten	Totaal	Gegeten	Totaal	Gegeten	Totaal	
Zwartneushaai	175	225			200	200			80	225					195
Zwartpunthaai	600	700			750	750			0	750					850
Zandbankhaaien	1500	2100			1000	2100			1350	2100					2450
Juveniele Zandbankhaaien	850	950			950	950			720	950					330
Tarpons, tandbaars, makreel	2600	2600			2600	2600			2600	2600					0
Barracuda's	600	750			450	750			0	750					1200
Roggen	1750	2000			250	2000			1950	2000					2050
Noordzee					110	260									150
Wrakbaarzen			625	625	120	150	120	545							455
Steuren			1215	1215	1075	1075									0
Murenen	300														7680
Totaal per dag		1250		0		3330		425		2675		0		0	
														7680	

Adding the totals of alle weekly overview yielded yearly totals. Contributions to the total of the species was also calculated.

Rest product totals			
Overal 2024	Average/week	Total year extrapolated	
349649	7947	413222	gr
349.65	8	413	kg

	Week days								
	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday	Control sum	
Total	114835	10779	93447	14058	102295	4004	10231	349649	gr
Extrapolated/total	135714	12739	110437	16614	120894	4732	12091	413222	gr
Average/week	2610	245	2124	320	2325	91	233	7947	gr
Average/week	2.61	0.24	2.12	0.32	2.32	0.09	0.23	7.95	Kg
Percentage	32.84%	3.08%	26.73%	4.02%	29.26%	1.15%	2.93%	100.00%	

Species			
Type	Total amount	Average/week	Percentage/total
Blacknose shark	16594	386	4.75%
Blacktip shark	50104	1165	14.33%
Sandbar sharks	98572	2292	28.19%
Juvenile sandbar sharks	54209	1261	15.50%
Tarpons, grouper, mackerel, barracud	39047	908	11.17%
Rays	27677	644	7.92%
North sea	9594	223	2.74%
Wreckfish	8764	204	2.51%
Moray eels	23514	547	6.73%
Kelp	19379	451	5.54%
Sturgeons	2195	51	0.63%
Control	349649	8131	100.00%
		Contribution of sharks	62.77%

Appendix D – Observations waste recycling at Blijdorp

The process of making gel feed works roughly as follows: About 300 grams of fish ingredients are used, with roughly equal amounts of each type. Then, 20 grams of agar are weighed and mixed with hot water coming from the Quooker. Since the Quooker water is said to not be at 100 degrees, the mixture is heated for another 1.5 minutes in the microwave. A kind of foam layer forms on the agar, this means it is ready and has a gel-like consistency. The agar is then placed in a container of water to cool it down more rapidly. It must cool below 50 degrees, otherwise the agar will damage the vitamins in the mixture. A mercury thermometer is inserted so the temperature can be determined. This is specifically a mercury thermometer because it can withstand higher temperatures.

Next, the container with fish leftovers is blended in a large measuring jug. I asked a question about removing hard pieces when blending. In practice, pieces are removed earlier in the fish kitchen so that less blending is needed.

While blending, we discussed that cooling the agar takes a long time and it is the slowest part of the production process. He often does something else simultaneously, such as cleaning items or preparing the vegan fish feed. When asked: in general, the longer you blend, the more homogeneous the paste becomes and the better the result. At the moment, he aims for an optimal balance between blending time and smoothness.

After blending, the fish mixture is poured back into the “bami container.” Once in the container, vitamin C and SharkVit powder are added, measured in scoops. These are mixed in with a spoon.

Once the agar has cooled sufficiently, it is poured onto the mixture. It is then stirred for quite a long time. It must be mixed thoroughly; otherwise, the agar does not combine well with the fish product. This step also seems to take quite a bit of time.

When everything is fully mixed, the mixture is placed in the refrigerator to “set.” On the day of feeding, the block is cut into pieces for feeding.

It is important to note that different people work in the fish kitchen each day, and many processes depend on the person working at that moment.

The agar serves as a binding agent, similar to what is often used in DIY fish feed by hobbyists; it can be water-stable, which helps keep it together.

Also discussed in the production process: the wet feed is only made on the days the sharks are fed. The next day, the wet feed is then used.They do not wait longer, as the products spoil quickly once defrosted.

At the moment, making the gel food takes quite a lot of time. Sometimes it is not made, and then a bit more of another product is fed instead.

DUMEA AGRO

A&P bemonsteringen

ANALYSERAPPORT

Overig (NCC Nat-Chemische analyse)

Carnivore Fish Feed

Monster en Onderzoek

Labnummer:		Monsterbenaming:	**Carnivore Fish Feed**
Opdrachtnummer:		Monstername door:	Opdrachtgever
d.d. monstername:	6 december 2021	Ruwvoer:	Overig
d.d. verslag:	24 december 2021	Status verslag:	Definitief

	Eenheid	Resultaat product	Resultaat droge stof
Droge Stof	g/kg	**142**	
Ruw Eiwit	g/kg	**73**	**514**
Ruw Vet	g/kg	**29**	**202**
Ruw Celstof	g/kg	**2**	**17**
Ruw As	g/kg	**24**	**170**
Zetmeel	g/kg		**11**
Suiker	g/kg		**15**
VC-OS	% OS		**90,2**
Ammonium	g/kg		**1,2**
Nitraat	g/kg		**0,9**
pH		**6,8**	

Mineralen en Spoorelementen	Eenheid	droge stof
Natrium	g/kg	**12**
Kalium	g/kg	**9,9**
Magnesium	g/kg	**2,6**
Calcium	g/kg	**18**
Fosfor	g/kg	**12**
Zwavel	g/kg	**9**
Chloor	g/kg	**19**

	Eenheid	Droge Stof
Mangaan (mg)	mg/kg	**5,4**
Zink (mg)	mg/kg	**56**
IJzer (mg)	mg/kg	**77**
Koper (mg)	mg/kg	**29**
Molybdeen (mg)	mg/kg	**0,68**
Borium (mg)	mg/kg	**32**
Kobalt (µg)	µg/kg	**110**
Seleen (µg)	µg/kg	**2500**

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Appendix F – Economic feasibility

Kg to be processed				
Viscera percentage	Not gutted	Gutted	Kg not gutted/ working day	Kg Gutted/ working day
18	15408	18790	61	74
Viscera percentage	Not gutted	Gutted	Kg not gutted/ working day	Kg Gutted/ working day
12	10272	11673	41	46

Type	Annual revenue $	Revenue/month $	Revenue/working day ($)
Non-branded dog kibble	51424	3968	188
Non-branded cat kibble	63052	4865	231
Non-branded wet dog food (canned)	164726	12710	603
Non-branded wet cat food (canned)	80580	6218	295

Kg/hour	# cans/year	# portions / working day
5.08	27392	108.3

Operator cost				
Salary machine operator/month ($)	Hourly rate ($)	Overhead	Hourly rate employer ($)	Daily cost machine operator ($)
1794	10	30	13	108

Machine payback		
Machine cost	Machine payback time/ years	Machine cost / working day ($)
3000	2	5.93

Rent	
Facility rent cost / month ($)	Facility cost / working day ($)
2014	96

Electricity						
Electricity usage (kWh / m^2)	Surface area (M^2)	Electricity usage/ year (kWh)	Price/ kWh ($)	Montly charge	Electricity cost/year ($)	Electricity cost / working day
219	109	23871	0.3136	43.79	8011.43	31.67

Water				
Water usage per employee/year (M^3)	Price / M^3 ($)	Monthly charge	Water cost / year ($)	Water cost / working day ($)
330	4.055	16.34	1534.23	6.1

Insurance		
Insurance / month ($)	Insurance/year ($)	Insurance / working day ($)
19.0	227.87	0.90

Own facility						
Total cost / working day ($)	Revenue/ working day ($)	Middle men cost	Profit/working day ($)	Profit/fisherman/working day ($)	Profit/fisherman/year ($)	Profit/fisherman/month ($)
247.73	603	120.6	234.56	4.69	1187	98.91

No facility only operator						
Total cost / working day ($)	Revenue/ working day ($)	Middle men cost	Profit/working day ($)	Profit/fisherman/working day ($)	Profit/fisherman/year ($)	Profit/fisherman/month ($)
145.23	603	120.6	337.05	6.74	1705.50	142.12

Appendix G – Pet feed pricing

September															Average	Price/Kg ($)
Brokjes - Hond - Niet-merkgebonden	1 Kg	4.25	4	3.59	3.8	3.95	3.85	3.25	3.2	3.5	3.35	2.9	3.35	3.5	3.58	3.58
Brokjes - Kat - Niet-merkgebonden	1 Kg	4.25	3.49	3.25	3.95	5.25			4.95					4.5	4.23	4.23
Nat voer - Hond - Niet-merkgebonden (Blik)	375 gr	4.5	2.95	1.49	1.7	2.95	2.95	3.5	3.59	2.95		2.95	3.5		3.00	10.9
Nat voer - Kat - Niet-merkgebonden (Blik)	280 gr		1.59	2.4		1.55			1.65	1.45	1.5				1.69	6.0

Augustus															Average	Price/Kg ($)
Niet-merkgebonden hondenbrokjes	1 Kg		3.5	4	4	3.8	4.45	3.5		3.2	3.5	3.35	3.1	5	3.76	3.76
Niet-merkgebonden kattenbrokjes	1 Kg	5.5	4.95	4.75	2.15	5.25		3.38	4.95	3.75	4.95	6.5			4.61	4.61
Niet-merkgebonden Nat voer hond	375 gr		4.5	2.95			2.95	3.59	2.95		2.95	3.5			3.34	12.2
Niet-merkgebonden Nat voer Kat	280 gr			1.58		1.55			1.65	1.25					1.51	5.4

April															Average	Price/Kg ($)
Niet-merkgebonden hondenbrokjes	1 Kg	5.95			3.6	4.35	3.5	3.25	3.22	3.4	3.65	2.74	3.1	3.95	3.70	3.70
Niet-merkgebonden kattenbrokjes	1 Kg		8.5		4.35			4.3		2.74	3.75	4.5			4.69	4.69
Niet-merkgebonden Nat voer hond blikjes	375 gr	4.5			3.19			3.2	2.95			2.95	3.5		3.38	12.3
Niet-merkgebonden Nat voer kat blikjes	280 gr			1.99					1.45	1.5					1.65	5.9

Types	Price/kg ($)	Revenue/Kg ($)
Non-branded dog kibble	3.68	3.41
Non-branded cat kibble	4.51	4.18
Non-branded wet dog food (canned)	11.79	10.92
Non-branded wet cat food (canned)	5.77	5.34

Appendix H – Automated agar making setup code

```
#include <OneWire.h>
#include <DallasTemperature.h>

// ----- DS18B20 SETUP -----
#define ONE_WIRE_BUS 2
OneWire oneWire(ONE_WIRE_BUS);
DallasTemperature sensors(&oneWire);

// ----- OUTPUT PINS -----
const int RELAY_PIN = 3;
const int MIXER_PIN = 4;

// ----- BUTTON PINS -----
const int BUTTON1_PIN = 5;   // Program 1: periodic mixing
const int BUTTON2_PIN = 6;   // Program 2: continuous mixing

// ----- RELAY LOGIC -----
const int RELAY_ON  = LOW;
const int RELAY_OFF = HIGH;
const int MIXER_ON  = LOW;
const int MIXER_OFF = HIGH;

// ----- CONTROL PARAMETERS -----
const float SETPOINT_TEMP_C = 50.0;
const float HYSTERESIS_C    = 0.2;

// ----- MIXER TIMING (PROGRAM 1) -----
const unsigned long MIXER_INTERVAL = 150000UL; // 2.5 min
const unsigned long MIXER_ON_TIME  = 15000UL;  // 15 s

// ----- PROGRAM STATES -----
enum ProgramState { OFF, PROGRAM_1, PROGRAM_2 };
ProgramState currentProgram = OFF;

// ----- GLOBAL STATES -----
bool heaterOn = false;
bool mixerOn  = false;
unsigned long lastMixerChange = 0;
```

```
void setup() {
  Serial.begin(9600);
  sensors.begin();

  pinMode(RELAY_PIN, OUTPUT);
  pinMode(MIXER_PIN, OUTPUT);
  pinMode(BUTTON1_PIN, INPUT_PULLUP);
  pinMode(BUTTON2_PIN, INPUT_PULLUP);

  digitalWrite(RELAY_PIN, RELAY_OFF);
  digitalWrite(MIXER_PIN, MIXER_OFF);

  Serial.println("Temperature,Setpoint");
}

void loop() {
  handleButtons();

  if (currentProgram == OFF) {
    digitalWrite(RELAY_PIN, RELAY_OFF);
    digitalWrite(MIXER_PIN, MIXER_OFF);
    heaterOn = false;
    mixerOn  = false;
    return;
  }

  // ----- TEMPERATURE -----
  sensors.requestTemperatures();
  float tempC = sensors.getTempCByIndex(0);
  if (tempC == DEVICE_DISCONNECTED_C) return;

  // ----- HEATER CONTROL -----
  if (!heaterOn && tempC < (SETPOINT_TEMP_C - HYSTERESIS_C)) {
    digitalWrite(RELAY_PIN, RELAY_ON);
    heaterOn = true;
  }
  else if (heaterOn && tempC > (SETPOINT_TEMP_C + HYSTERESIS_C)) {
    digitalWrite(RELAY_PIN, RELAY_OFF);
    heaterOn = false;
```

```

  // ----- MIXER CONTROL -----
  if (currentProgram == PROGRAM_2) {
    digitalWrite(MIXER_PIN, MIXER_ON);
    mixerOn = true;
  }
  else if (currentProgram == PROGRAM_1) {
    periodicMixer();
  }

  // ----- SERIAL PLOTTER -----
  Serial.print("Temperature:");
  Serial.print(tempC);
  Serial.print(",Setpoint:");
  Serial.println(SETPOINT_TEMP_C);

  delay(1000);
}

// ============================================================
// BUTTON HANDLING (EDGE-DETECTED TOGGLE)
// ============================================================
void handleButtons() {
  static bool lastB1 = HIGH, lastB2 = HIGH;

  bool b1 = digitalRead(BUTTON1_PIN);
  bool b2 = digitalRead(BUTTON2_PIN);

  if (lastB1 == HIGH && b1 == LOW) toggleProgram(PROGRAM_1);
  if (lastB2 == HIGH && b2 == LOW) toggleProgram(PROGRAM_2);

  lastB1 = b1;
  lastB2 = b2;
}
```

```
// ============================================================
// PROGRAM TOGGLE
// ============================================================
void toggleProgram(ProgramState selected) {
  if (currentProgram == selected) {
    currentProgram = OFF;
  } else {
    currentProgram = selected;
  }

  // Reset mixer state on ANY transition
  digitalWrite(MIXER_PIN, MIXER_OFF);
  mixerOn = false;
  lastMixerChange = millis();
}

// ============================================================
// PERIODIC MIXER (PROGRAM 1 ONLY)
// ============================================================
void periodicMixer() {
  unsigned long now = millis();

  if (!mixerOn && (now - lastMixerChange >= MIXER_INTERVAL)) {
    digitalWrite(MIXER_PIN, MIXER_ON);
    mixerOn = true;
    lastMixerChange = now;
  }

  if (mixerOn && (now - lastMixerChange >= MIXER_ON_TIME)) {
    digitalWrite(MIXER_PIN, MIXER_OFF);
    mixerOn = false;
    lastMixerChange = now;
  }
}
```

Appendix I – FRP-system prototype walkthrough

Interview questions

Agar
What is your impression of the way the agar is produced?
Do you think the process of producing agar in this way is more reliable?
Do you think keeping the agar warm in this way would result in time savings?
Would integrating the cooking and mixing process be beneficial for you?

Size reduction
What is your first impression of the process of producing different sizes?
What do you think of the consistency of the block?
Do you think these three sizes would be sufficient to feed all fish species within the oceanarium?
Do you think the sizes produced here would be sufficient for the aquaculture industry?

Mixing of residues
What is your first impression of the process of mixing fish residues and vitamins?
Do you think the mixing process is more homogeneous than the process you currently use?

General
Do you have any general comments on the process?
Are there any important aspects that are not considered in this process?

Records of walkthrough

Process walkthrough
Making the agar on the induction plate went well. After this, it was placed on the heated plate with the temperature probe placed in the middle. In the meantime, the cutting of an agar–fish residue block was demonstrated. From this, well-shaped cubes and shavings were created. After demonstrating the cutting process, we returned to the agar cooling process. Unfortunately, it had cooled down too far to 43 degrees. Because of this, the agar was already starting to set. Mixing in the remains did not go well, it set too quickly. Because of this, the process was stopped. The rest of the process therefore was explained verbally.

Follow-up discussion after making the feed
Making the agar in this way with the induction plate is much safer. It is nice that everything is in one place and that you do not have to walk back and forth with hot substances. Furthermore, he was surprised that you do not have to cook it for that long at all to get a good consistency. When the agar becomes slightly thicker, it is already prepared well enough.

He also indicates that he likes the use of a metal pan. Not only because of good heating and cooling, but also because metal is much more hygienic. In plastic, a lot of residual material remains, while metal is much easier to clean. He also indicates that he would find it nice if the feed could be made and then directly distributed to the fish.

He has not seen a working example of keeping the agar at 50 degrees, but does indicate that it would be nice if this works. This way, you do not have to redo any work in case you unintentionally let it cool down too far. He does note that if the agar is left open for a longer time, bacterial growth might occur in the pan. Completely integrating the whole so that heating and mixing are in one device seems like a good idea to him.

When it comes to size, he indicates that feeding different sizes is useful. They currently feed fish starting from 9 centimeters. With smaller feed, you could also start feeding fish of 1 to 3 centimeters. In this context, he indicates that the shaved material certainly increases the applicability of the feed. When asked further whether smaller is his preference, he indicates that it can always be smaller. However, it is also a matter of testing whether it works and how well it works. In this, the moment of feeding is of course also important; at the beginning of the day, they will eat it more easily than completely at the end.

The consistency of the agar block that was made is comparable to what is normally made by the animal caretakers, and this stands out to him a lot. When it comes to mixing, he indicates that continuous mixing might be better than interrupting the mixing. This test failed because it had become too cold. Mixing also has a good application for adding medication for fish by adding this to the mixture.

In general, he indicates that he would prefer not to have a probe, as it gets in the way and becomes contaminated. It is also not very fail-safe. We did come up with the idea of possibly using a laser to measure the temperature of the agar. This might measure better. He also indicated that for shaving, a funnel and a pushing stick are really needed. After this, he briefly philosophized about making feed and then feeding immediately afterward. This could, for example, be done by feeding the sharks earlier and thus also having remains earlier. He wonders whether this is technically feasible for the staff.

Personal Project Brief – IDE Master Graduation Project

Name student Lucas Frantzen **Student number** 4836014

PROJECT TITLE, INTRODUCTION, PROBLEM DEFINITION and ASSIGNMENT
Complete all fields, keep information clear, specific and concise

Project title Fishmeal free by 2030

Please state the title of your graduation project (above). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

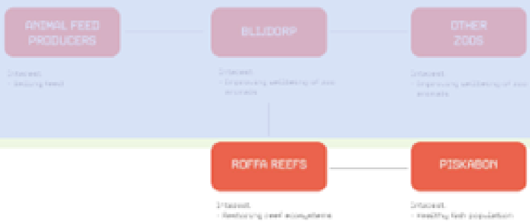
Introduction

Describe the context of your project here; What is the domain in which your project takes place? Who are the main stakeholders and what interests are at stake? Describe the opportunities (and limitations) in this domain to better serve the stakeholder interests. (max 250 words)

The project is setup by Blijdorp zoo. Blijdorp makes an effort to be involved in wildlife preservation. One of their programmes is Roffa Reefs. Roffa Reefs is set up by Sander van Lopik, a field technician at the zoo. With Roffa Reefs Sander wants to restore reef ecosystems, focusing on the role of fish. Roffa Reefs believes it is important to work with local fishermen in this effort, since they are a key part of the ecosystem. They started collaborating with Bonairean fishing cooperative Piskabon. The next step for Roffa Reefs is to have tools to monitor fishing on Bonaire. To do this an incentive has to be created for fishermen to bring back their residues after cleaning the fish.

Roffa Reefs works directly with Blijdorp zoo. At the zoo they are looking to improve animal welfare. One element they are looking at is the animal feed. Currently they are feeding what they have available, not necessarily what is optimal for the animals. They are looking for improved feed that serves animals better. In the project we aim for a solution that tackles both problems in one system.

In figure 1 an overview can be found of all stakeholders and their interest. It is a unique opportunity to directly work with local fishermen, as they are often seen as the culprit of the decline of reef ecosystems. Blijdorp is also in direct contact with feed producers and other zoos, giving the opportunity to promote solutions on a broader scale.



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Personal Project Brief – IDE Master Graduation Project

Problem Definition

What problem do you want to solve in the context described in the introduction, and within the available time frame of 100 working days? (= Master Graduation Project of 30 EC). What opportunities do you see to create added value for the described stakeholders? Substantiate your choice.
(max 200 words)

Blijdorp is currently feeding fishmeal to zoo animals. The fish species contained in the fishmeal are unknown, and there are suspicions that endangered species may be present. Additionally, in the process of creating fishmeal, nutrients such as vitamins and omega-3 fatty acids are lost.

Blijdorp has started working on an alternative, creating wet feed that preserves nutrients by binding fish residues to agar. Further development of this process is needed to implement nutrient-rich and traceable feed at Blijdorp, thereby boosting animal welfare.

Roffa Reefs has also noticed that local fishermen on Bonaire are throwing fish residues back into the sea. These residues could be turned into wet feed, creating an additional revenue stream for fishermen. The fish feed system can be provided to fishermen, empowering them to implement it through their local government. Additionally, DNA testing can be incorporated into the wet feed production system, supporting Roffa Reefs' ecosystem restoration efforts.

Assignment

This is the most important part of the project brief because it will give a clear direction of what you are heading for. Formulate an assignment to yourself regarding what you expect to deliver as result at the end of your project. (1 sentence) As you graduate as an industrial design engineer, your assignment will start with a verb (Design/Investigate/Validate/Create), and you may use the green text format:

Create a prototype of a system that turns fish residue into wet fish feed to validate its viability as an additional revenue stream for local fishermen on Bonaire, and as a system to recycle fish residues at Blijdorp.

Then explain your project approach to carrying out your graduation project and what research and design methods you plan to use to generate your design solution (max 150 words)

I plan to start with a literature review combined with interviews with fishermen on Bonaire, feed experts, and animal welfare experts at Blijdorp. I would like to investigate interview methods to ensure this is done correctly.

An important part of the project is to empower local fishermen. Extensive literature is available on the topic of empowerment through design. I want to explore this literature to identify the best methods to apply.

Project planning and key moments

To make visible how you plan to spend your time, you must make a planning for the full project. You are advised to use a Gantt chart format to show the different phases of your project, deliverables you have in mind, meetings and in-between deadlines. Keep in mind that all activities should fit within the given run time of 100 working days. Your planning should include a ***kick-off meeting, mid-term evaluation meeting, green light meeting*** *and* ***graduation ceremony.*** *Please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any (for instance because of holidays or parallel course activities).*

Make sure to attach the full plan to this project brief.
The four key moment dates must be filled in below

Kick off meeting	18 Sep 2025
Mid-term evaluation	07 Nov 2025
Green light meeting	2 Jan 2026
Graduation ceremony	30 Jan 2026

In exceptional cases (part of) the Graduation Project may need to be scheduled part-time. Indicate here if such applies to your project

Part of project scheduled part-time	
For how many project weeks	
Number of project days per week	

Comments:

Motivation and personal ambitions

Explain why you wish to start this project, what competencies you want to prove or develop (e.g. competencies acquired in your MSc programme, electives, extra-curricular activities or other).

Optionally, describe whether you have some personal learning ambitions which you explicitly want to address in this project, on top of the learning objectives of the Graduation Project itself. You might think of e.g. acquiring in depth knowledge on a specific subject, broadening your competencies or experimenting with a specific tool or methodology. Personal learning ambitions are limited to a maximum number of five.
(200 words max)

Many projects throughout my master's have revolved around creating designs that generated extra revenue for company X or Y. For my graduation, I wanted to do something more purposeful. This project could have a positive impact on reef ecosystems, local fishermen, and the feed industry, which I am very excited about. Through this project, I want to explore whether I would like to continue creating designs with direct impact, rather than working at a large (design) firm.

One of the competencies I want to develop is prototype building. Throughout my studies, I have developed various prototypes, most of which ended in an incomplete state. In this project, I want to develop a system that reaches a stage where it can be tested and validated. Additionally, I want to improve my social design skills. As mentioned, we want to empower local fishermen, and I still have a lot to learn on this topic.

My biggest personal ambition is improving my planning. I often make extensive plans, but I rarely manage to plan in a way that prevents me from experiencing high levels of stress. This is probably due in part to my personality, but I would like to execute this project in a structured and calm manner.