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The potential incorporation of locally available alternative and novel ingredients into fish feed in East Africa

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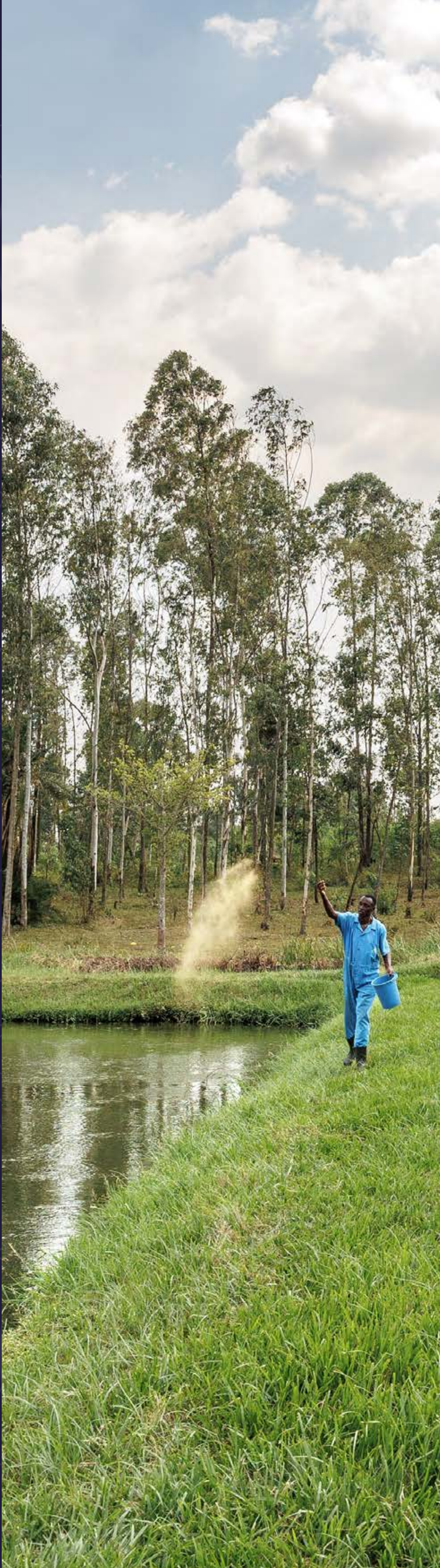
Contents

Glossary

AA	Amino Acids
ANF	Anti-nutritional factor
BSF	Black soldier fly
BY	Brewer’s Yeast
DCP	Dicalcium Phosphate
EA	East Africa(n) (Uganda, Kenya, Tanzania and Rwanda)
EAA	Essential Amino Acids
FCR	Feed Conversion Ratio
FM	Fish Meal
FWS	Freshwater Shrimp
KI	Key informant
LCA	Life Cycle Assessment
(M)MT	(Million) Metric Tonnes
PAP	Processed Animal Proteins
PM	Peanut Meal
PPM	Parts per Million
Shadow price	The price at which an ingredient can be economically included in a formulation
SWOT	Strength, Weaknesses, Opportunities and Threats
	United Republic of Tanzania
TMT	Thousand Metric Tonnes
TRL	Technology Readiness Levels



Executive Summary

The countries of East Africa (EA) have set ambitious targets for the expansion of the aquaculture sector. Tilapia, being the main cultured species, faces significant challenges in the industry's expansion, primarily due to the availability of affordable feed. Tilapia feeds typically consist of a blend of around ten ingredients that provide essential nutrients. Since these ingredients contribute significantly to feed costs, it is crucial to understand current market status to support the development of the aquaculture industry. This study explored novel or alternative ingredients that could be scaled within the East African context.

The assessment was conducted through a combination of desk research and consultations with key informants from various sectors including industry, academia, and policy. Ingredients are classified based on their functionality within the diet, such as protein, energy, carbohydrate, and supplement. Technology Readiness Level assessed the maturity of novel and alternative ingredients with respect to preparedness for mainstream commercial adoption. Using linear programming software, least-cost formulations were conducted based on conventional ingredients and nutritional requirements. Prices of key ingredients were updated to reflect market rates, providing foundational data for evaluating alternative and novel ingredients in terms of cost-effectiveness and nutritional balance.

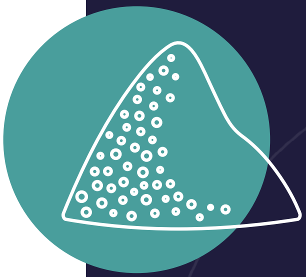
Alternative Ingredients

Potential alternative ingredients, produced from by-products with interesting nutritional characteristics, such as **canola, rapeseed meals** and **distillers dried grain and solubles (DDGS),** are globally traded but currently not produced or used in tilapia feeds in EA. **Peanut meal**, which is a by-product resulting from the extraction of oil from peanut seeds, is already produced in EA and considered a valuable source of essential fatty acids. **Sorghum** functions as a contributor of starch and energy source in aquafeeds, but processing into aquafeed requires more energy compared to corn and wheat. Contrary, agricultural production of sorghum thrives in a variety of climates and doesn't require a lot of resources in the form of water and fertiliser compared to wheat and corn. Most of the supply in Uganda, Kenya and Rwanda is locally accessible, but more demand by a growing population and other industries (e.g., livestock) might lead to increased food-feed competition. Overall, DDGS shows interesting feed ingredient characteristics with relatively high inclusion levels combined with an attractive price followed up by sorghum as a possible replacement for corn.

It is important to consider that some of these crops and derived ingredients contain anti-nutritional factors (ANFs) and require processing (e.g., heat) before being included in aquafeeds. Other important considerations are proper storage conditions to maintain quality and avoid issues, such as fungi contamination.

Shrimp meal is a bycatch of silver cyprinid fisheries and is locally available. The separation and processing into shrimp meal lacks industrialisation, indicating significant potential to reduce discards, enhance utilisation and quality preservation. Given the potential high cost, it could function as a feed additive to enhance palatability.

Canola, rapeseed meals



Distillers dried grain with solubles

Peanut meal

Sorghum

Shrimp meal

Brewer's yeast

Black soldier fly

Duckweed

Novel Ingredients

As a novel feed ingredient, **brewer's yeast** shows interesting nutritional characteristics, especially in regard to its protein content (high digestibility and balanced amino acid profile). However, its use in aquafeed requires facilities to process wet brewer's by-products into dry meals. Price points are relatively high (comparable to animal by-products) and therefore brewer's yeast shows potential as a feed additive with low inclusion levels or in starter feeds to partly replace fishmeal.

Black soldier fly contains high protein levels and well-balanced amino acid composition, which are superior to plant proteins. While fat levels are also high, the deficiency of essential fatty acids functions as a limiting factor for its inclusion in aquafeeds. Additionally, supply is limited, and prices are significantly higher compared to all other ingredients, which is mainly caused by inefficient collection and use of waste to feed larvae. Overcoming these barriers might be an opportunity for domestic EA production, which is currently non-existing.

Duckweed is an excellent source of essential amino acids (e.g., lysine and methionine) and micronutrients. Tilapia is known to efficiently convert duckweed to biomass. Nevertheless, its use on a commercial scale is limited by its high water content, which makes drying costly and time consuming.

Of all the novel feed ingredients assessed, brewer's yeast shows promising potential as a tilapia feed ingredient from a nutritional and price perspective. Black soldier fly needs a significant price reduction to become economically viable, while price and high-water content functions as a bottleneck for duckweed.

Locally Sourced Feed Innovations

In selecting feed ingredients for aquaculture, it is crucial to prioritize locally sourced options with minimal environmental impact and no competition with human food. This ensures sustainability and economic viability while meeting nutritional needs. Fishmeal, despite its cost, is strategically included in tilapia feed formulations to enhance consumption, digestibility, and overall fish welfare, balancing micro- and macronutrient levels.

Feed provisioning plays a pivotal role in the sustainability of aquaculture, impacting production costs, profitability, and environmental outcomes. While tilapia feed formulations in EA utilize various ingredients, careful consideration is needed to mitigate environmental concerns associated with both animal and plant-derived feed sources. Each ingredient has its own set of impacts, necessitating a thorough evaluation to optimize socio-economic and environmental performance.

This report thoroughly examines ingredients available to the aquafeed industry in EA, noting higher costs compared to global averages, especially for imports due to increased transportation expenses. Evaluation criteria to finally recommend products for future investment and investigation, include economic value, safety, availability, and technological maturity of production methods and raw materials. After our thorough assessment, we identified four high-potential ingredients for aquafeeds, all producible within EA. Additionally, locally producing rendering products, particularly from poultry, shows promise in making crucial ingredients more affordable.

Brewer's yeast: derived from brewery by-products, offers cost-effective and high-quality feed enhancement potential for aquafeeds in EA, with a potential revenue of $7 million USD if hurdles in aggregation can be overcome.

Peanut meal: despite underutilization due to mycotoxin contamination, holds promise with safe treatment methods and further research to bridge the gap in understanding its nutritional potential and promoting acceptance among feed millers.

Freshwater shrimp: an underutilized resource in EA despite its abundance in Lake Victoria, requires improved fishing practices and processing facilities to capitalize on its potential as an ingredient in aquafeeds, particularly for starter feeds.

Sorghum: as a low-cost carbohydrate source, presents an alternative to maize in aquafeeds, but careful selection of suitable varieties is necessary to ensure nutritional suitability and economic competitiveness.

Processed Animal Proteins (PAPs): offer potential local, cost-effective crude protein sources for aquafeeds in EA. Scattered production of animal by-products due to fragmented livestock industries and a lack of proper machinery hinder current production and utilization, necessitating locally available processing technologies to address challenges and enhance cost-effectiveness.

Brewer's yeast

Peanut meal

Freshwater shrimp

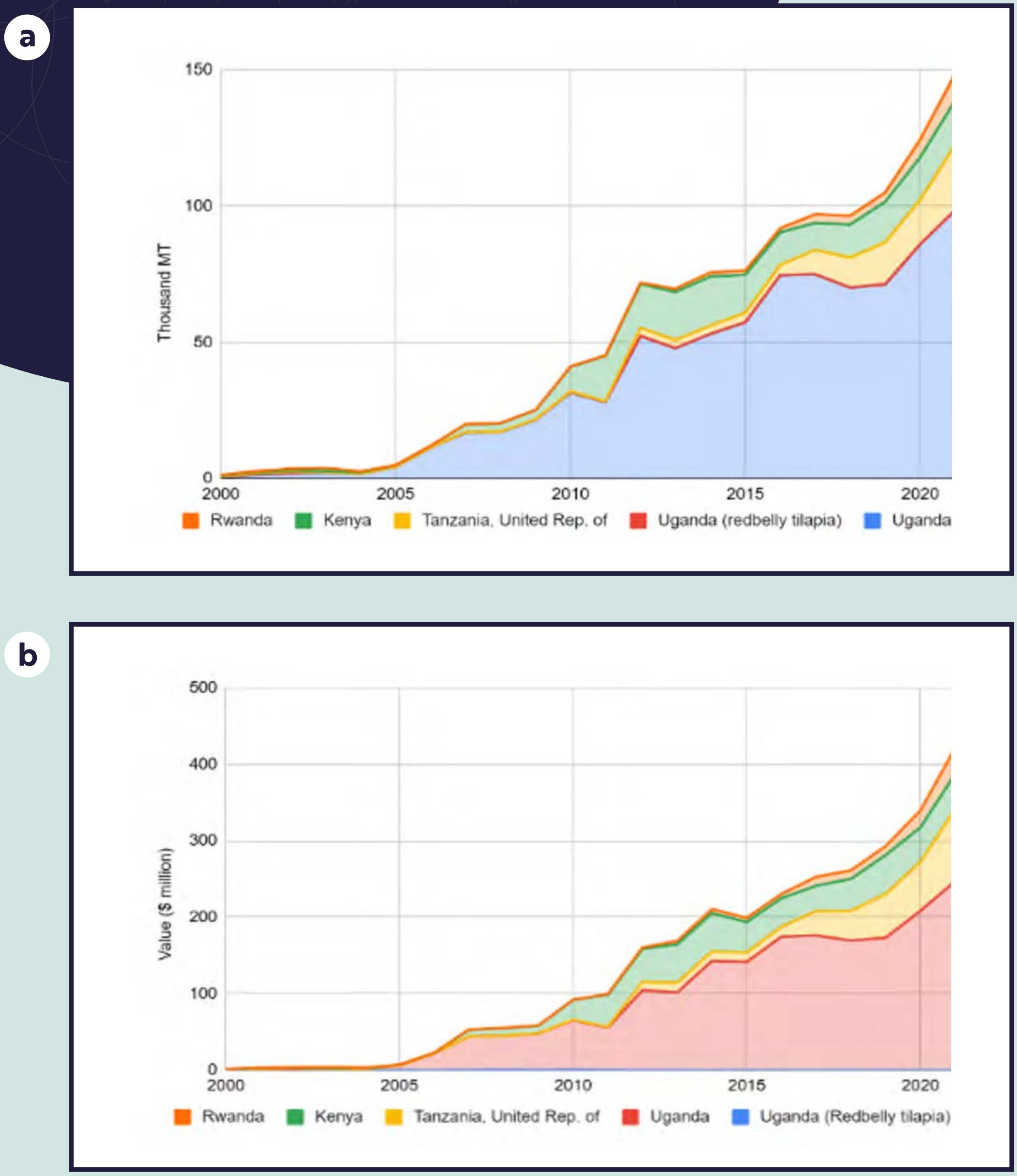
Sorghum

Processed Animal Proteins

1. Introduction

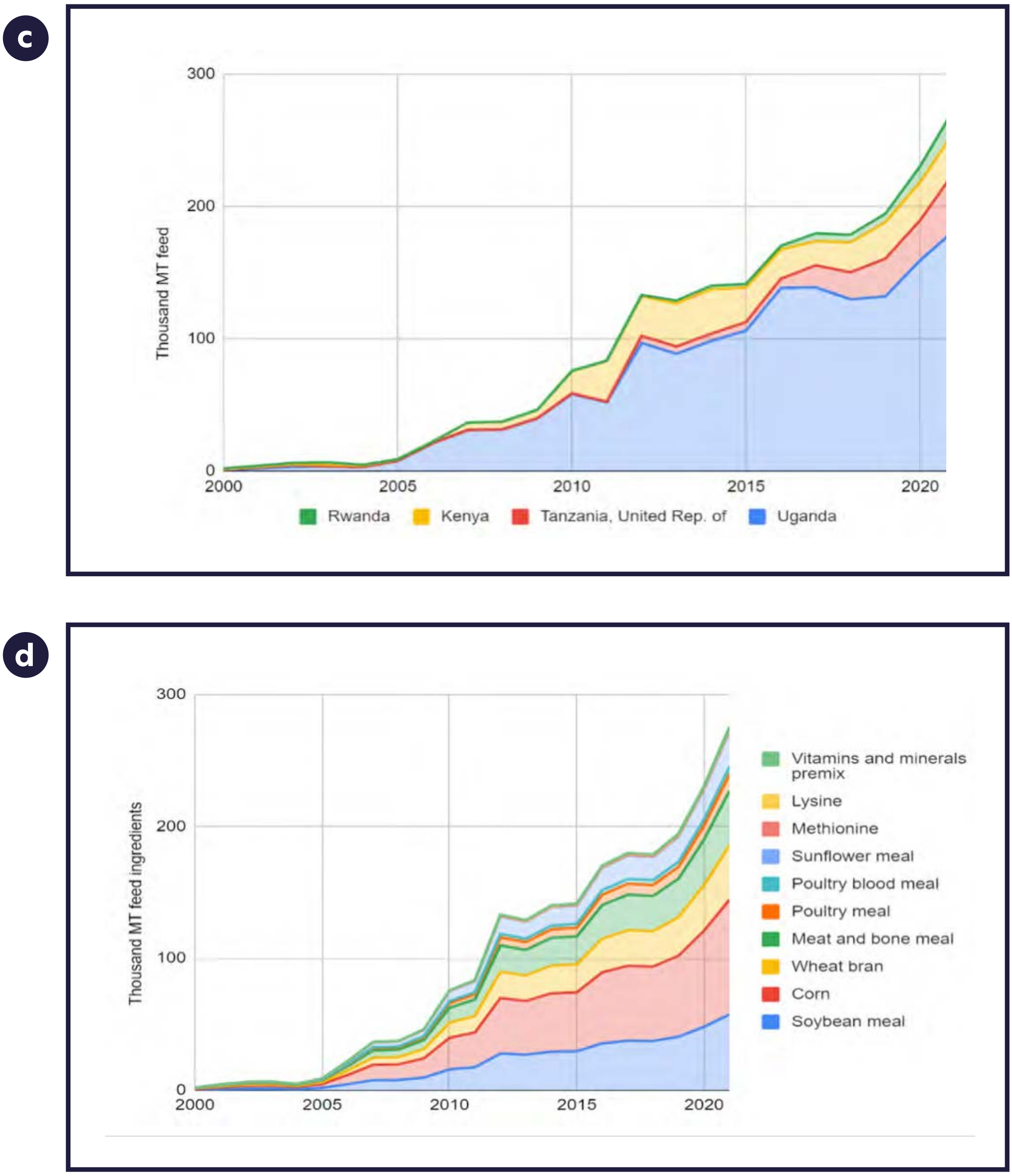
The East African (EA) community member states have identified the potential of fish farming to offer a low-carbon, high-quality protein source for national consumption and export markets, critical to meet future food demands (Willett, 2019). Uganda, Kenya, Tanzania and Rwanda currently produce a total of 149 thousand metric tonnes (MT) (Figure 1a) with a value of $422 million (Figure 1b).

Figure 1. Total production (a) and value of Nile Tilapia (b) in EA (FAO, 2023).



EA countries have set ambitious targets, to produce significant volumes of farmed fish in the coming decades, with the region collectively targeting production in excess of 1 million MT by 2035. Several barriers will need to be overcome to achieve this goal; feed being a significant one given that it typically makes up the bulk of production costs in most aquaculture systems. Fish feed demand in EA in 2021 was around 275,000 MT (Figure 2). For the region to achieve its scale ambitions, feed production will need to reach in excess of 1.85 million MT in annual production by 2035 (based on an average FCR of 1.85) (Ofori et al., 2009; El-Sayed, 2013; Te Velde et al., 2022).

Figure 2. Estimated EA feed (c) and ingredient (d) demand between 2000 and 2021. Ingredient demand is based on a typical grow-out tilapia feed formulation (Table 25).



Access to quality and commercially competitive fish feeds is critical for successful aquaculture because feeds constitute at least 50% of aquaculture production costs (Rana, Siriwardena and Hasan, 2009), even up to 70% in EA (Kubiriza, 2017). Presently, according to a key informant, three quarters of the fish feeds used in EA are imported, with only one quarter locally made. Imported feeds are expensive and associated with complex logistical challenges, being inaccessible to most fish farmers, especially small- and medium-scale producers. Locally made feeds differ in quality – some of them produced with designated machinery, while others are produced as mash using more traditional methods. The ambitious plans of producing substantial volumes of farmed tilapia in the region requires intensified local production of quality, commercially competitive feeds. Globally, successful feed production is anchored in accessing the necessary volumes of a range of quality raw materials, at commercially competitive prices.

The primary fish species cultured in EA is Nile tilapia (Oreochromis niloticus), which is also native to large areas of the region. This fish is known for its omnivorous nature, enabling it to efficiently digest both plant and animal origin ingredients. This characteristic makes tilapia relatively cheaper to feed compared with carnivorous fish, such as African catfish. The nutritional requirements of tilapia change throughout the culture cycle, starting at 48% protein for starter feeds and decreasing to 25-30% protein for grow-out feeds, with an estimated Feed Conversion Ratio (FCR) of 1.85 depending on the culture method (Ofori et al., 2009; El-Sayed, 2013; Te Velde et al., 2022). Considering the combined production targets of tilapia amongst the EA countries between 2025 and 2035, total feed demand is estimated at 3.4 MMT, in which the respective ingredient volumes are shown in Table 1.

Table 1. Estimated feed ingredient volumes (thousand metric tonnes (TMT)) to meet predicted production targets, based on a typical grow-out tilapia feed formulation as shown in Table 10 (personal information)

Ingredients	Inclusion (%)	TMT
Soybean meal	20.9	709
Corn	31.6	1,072
Wheat bran	15	509
Meat and bone meal	15	509
Poultry meal	4.6	156
Poultry blood meal	2	68
Sunflower meal	10	339
Methionine	0.2	7
Lysine	0.5	17
Vitamins and minerals premix	0.3	10
Total	**100**	**3396**

Table 1 illustrates that the expansion of aquaculture production will necessitate significant quantities of specific raw materials. The ingredients shown in Table 1 are currently available in EA, sourced either locally, imported from neighbouring countries, or imported from elsewhere. However, there is uncertainty regarding whether the current availability of these ingredients can sustain the local production of fish feed. Hence, identifying locally available, accessible, and suitable feed ingredients for tilapia feeds in EA is imperative (Messeder, 2019). Furthermore, diversifying the range of available ingredients by incorporating overlooked ones can reduce risk and cost, while enhancing the sustainability of local production. These potential ingredients may include those commonly used globally in aquafeeds, but not yet in EA (alternative ingredients); or those not currently utilised in aquafeeds, but with the potential to serve as ingredients (novel ingredients).

A typical formulation for fish, including tilapia, comprises a blend of over 10 different ingredients, each contributing one or more essential nutrients. In practice, ingredients are roughly categorised according to their primary nutritional contribution. Those with a protein content of ≥ 20% CP are considered protein sources. Ingredients with high carbohydrate levels (>40%) are primarily used as binders and, to some extent, as energy sources, while oils and fats serve as pure energy sources. Vitamins and minerals are usually added in small volumes through premixes (which will not be discussed in this report).

The principal goal of this report is to investigate novel or alternative ingredients that could potentially lower costs or enhance the quality of fish feed production in EA. Their potential contribution is evaluated by analysing their feasibility considering the challenges (technical, commercial, and nutritional) for their commercialisation as ingredients. A short list of the most promising ingredients is included.

2. Methodology

The assessment was conducted through a blend of desk research and consultation with a range of Key Informants (KIs) from industry, academia and policy. The novel and alternative ingredients list was refined and analysed, including consideration of the Technology Readiness Level (TRL), to create the final recommendations of innovative products that could provide future local inputs to the growing feed industry.

The study produces general recommendations for ingredients appropriate for large commercial feed millers. Some ingredients not included in final recommendations may be of use to small millers/farm made feeds. The report will not deliver a simple yes/no list of potential ingredients because of the complexity of decision making. It serves as a comprehensive tool assessing nutritional, technological, market (supply and demand) and other key considerations to inform potential selection and scale-up of these ingredients in EA.

2.1. Preparation of the long list of ingredients

The ingredient list is based on literature research, multiple internal meetings, and KI discussions (Table 2). Ingredients are classified based on their core function within the diet such as protein, supplement, energy, carbohydrate, binding, filler, palatability and microelements. We propose the use of two categories throughout the report to distinguish the different ingredients in terms of their implementation in the industry.

- Alternative: Ingredients new to EA, but used elsewhere in the fish feed industry
- Novel: Ingredients not frequently used in fish feeds

Table 2. List of alternative and novel ingredients that were initially considered.

Ingredient	Use	Ingredient purpose
Canola meal	Alternative	Protein
Corn gluten meal	Alternative	Protein
Distillers Dried Grains with Solubles (DDGS)	Alternative	Protein
Fishmeal (Peruvian anchoveta) (Engraulis ringens)	Alternative	Protein
Freshwater shrimp (Caridina nilotica)	Alternative	Protein
Peanut meal	Alternative	Protein/supplement
Sorghum	Alternative	Carbohydrate/energy/binding
Wheat gluten	Alternative	Protein
Black soldier fly (BSF)	Novel	Protein
Croton nut**	Novel	Protein/supplement
Duckweed (Lemna minor)	Novel	Protein, microelements
Hemp	Novel	Protein/supplement
Seaweeds***	Novel	Energy/Carbohydrate
Single Cell Proteins***	Novel	Supplement/Filler
Water morning glory (Ipomoea aquatica)****	Novel	Supplement/Filler
Yeast from brewer's waste	Novel	Protein, palatability

***Waste stream from oil production (biofuel). Grows on trees in semi-arid areas.*

****One potential option for increasing the amount of Omega-3 available to human populations is to exploit the endogenous ability of freshwater fish species to produce EPA and DHA from ALA using feed ingredients*

*****Already grows in Lake Victoria (see SNIFF project), already used in Vietnam for human food.*

Additives are used in very small quantities within animal feed and their usage is therefore too small to offer meaningful changes to feed manufacture. Additives would include Dicalcium Phosphate, DL-Methionine, Ethoxyquin and Lysine sulphate as well as Vitamins and mineral premix.

2.2. Refinement of the long list of ingredients

The adoption and scale of different ingredients faces a multitude of challenges, including but not limited to, nutrition, availability, cost, processing, legislation and environmental impact. To select the ingredients best suited for further exploration, a traffic light system (Table 3) using a wide range of criteria (Table 4) was used. This system identifies the industry bottlenecks for specific ingredients and focus areas for improvement.

Table 3. Traffic light system on removed ingredients with challenges highlighted. Ingredients that were subsequently removed are scored through.

- 🟩 No major challenges with the use of this ingredient in fish feed
- 🟨 Minor challenges with the use of this ingredient in fish feed
- 🟥 Major challenges with the use of this ingredient in fish feed

	Fish level			Feed mill level		National level		Wider impact		
	Nutritional composition	Protein Digestibility	Palatability	Processing and handling	Availability and Cost	Quality and safety	Legislation	Enwvironmental Impact	Competing uses	Research and Evidence
Canola meal	🟩	🟩	🟩	🟩	🟥	🟩	🟨	🟩	🟥	🟨
~~Corn Gluten meal~~	🟩	🟩	🟩	🟩	🟥	🟩	🟩	🟩	🟨	🟩
DDGS	🟩	🟩	🟩	🟨	🟥	🟩	🟨	🟩	🟩	🟨
~~Fishmeal (Peruvian anchoveta)~~	🟩	🟩	🟩	🟩	🟥	🟩	🟨	🟨	🟨	🟩
Freshwater shrimp	🟩	🟨	🟩	🟨	🟨	🟨	🟩	🟥	🟨	🟥
Peanut meal	🟩	🟨	🟩	🟨	🟨	🟨	🟩	🟩	🟨	🟨
Sorghum	🟩	🟩	🟨	🟨	🟨	🟨	🟩	🟩	🟨	🟨
~~Wheat gluten~~	🟩	🟩	🟩	🟩	🟥	🟩	🟩	🟩	🟨	🟩
Black soldier fly	🟩	🟩	🟩	🟨	🟥	🟨	🟩	🟩	🟩	🟨
~~Croton nut~~	🟩	🟨	🟨	🟥	🟥	🟥	🟩	🟨	🟨	🟥
Duckweed	🟩	🟩	🟩	🟥	🟥	🟩	🟩	🟩	🟩	🟨
~~Hemp~~	🟨	🟨	🟨	🟨	🟥	🟨	🟥	🟨	🟨	🟥
~~Seaweeds~~	🟨	🟨	🟨	🟥	🟥	🟩	🟩	🟩	🟩	🟨
~~Single Cell Proteins~~	🟩	🟩	🟨	🟨	🟥	🟨	🟥	🟩	🟩	🟥
~~Water morning glory~~	🟥	🟥	🟨	🟥	🟥	🟩	🟩	🟩	🟩	🟨
Yeast from brewer's waste	🟩	🟩	🟩	🟥	🟥	🟩	🟩	🟩	🟨	🟨

Table 4. Analysis considerations.

Level of impact	Analysis consideration	Description
Fish level	Nutritional Composition	Ingredients assessed for nutrient content and usability, based on the level of protein, carbohydrates, fats, vitamins, minerals, fibre content and anti-nutritional Factors (ANF).
	Protein Digestibility	Published data on the digestibility (for tilapia) of each ingredient, which determines the proportion of protein (more so protein/amino acids) that can be absorbed and utilised.
	Palatability	Fish prefer feeds containing ingredients they find palatable, leading to better feed intake and performance.
Feed mill level	Availability and Cost	The ingredient's availability in the local market or production area and its cost effectiveness, including seasonality, storage needed, volumes.
	Processing and Handling	Ease to store and transport, perishability, and ready incorporation into feed formulations provides efficiency in feed production. This includes the cost of manufacturing ingredients and the opportunities and challenges for scaling.
National level	Legislation	Details on tax (on imports), current relevant legislation, currency, infrastructure/ accessibility of feed sourcing.
	Quality and Safety	Quality and safety, including levels of contaminants, levels of toxins or anti-nutritional factors, and compliance with regulatory standards for feed production.
Wider impact / global level	Environmental Impact	The environmental literature on LCA, including land, water and carbon footprint, impact of the different ingredient's production and sourcing, where this data exists.
	Research and Evidence	Existence of scientific research, studies, and evidence supporting the use of the competing ingredients in fish feeds. Documented benefits, efficacy, and safety data of the ingredient.
	Competing uses	Different ingredients will be assessed on competing uses, because this escalates the cost and limits the availability of a given ingredient for fish feed production.

2.3. Deep dive for the final list of ingredients

A total of eight ingredients were removed once they had been assessed through the traffic light system (Table 3 and 4). This was because of 'red' challenges around their suitability in critical areas, such as availability and cost, quality and safety or legislative reasons. Table 5 explains the reasons for these removals in greater detail.

Table 5. Detailed rationale as to why specific ingredients were removed.

Ingredient	Reason for removal
Corn gluten meal	This ingredient possesses a high protein content and comes at a relatively high cost to manufacturers. Globally, due to this factor, it is not frequently utilised in the production of tilapia feeds, which typically have lower protein levels and are sold at lower prices. Significant cost reductions would need to be achieved to make this ingredient commercially viable.
Fishmeal	Incorporating this ingredient into tilapia grow-out feeds is cost-prohibitive and it is not routinely used in tilapia feeds in other regions. This is primarily fishmeal from wild catches of Peruvian anchovy.
Wheat gluten	This ingredient possesses a high protein content and comes at a relatively high cost. Due to this factor, globally, it is not frequently utilised in the production of tilapia feeds, which typically have lower protein levels and are sold at lower prices.
Croton nut	Untreated croton seeds are harmful to fish and offer no discernible nutritional advantages. Crotonoleic acid, which is a mixture of croton resin with inactive fatty acids, is a powerful irritant to the intestinal mucosa. The process of detoxifying this product is still in the early stages of development.
Hemp	A plant by-product lacking evident advantages, with low protein content and notably high fibre levels. Its legal status remains uncertain and is considered sensitive in numerous countries.
Seaweeds	An umbrella term that covers a range of species. Seaweed usage within tilapia feeds is still being researched and is at the early stage of development. Effective integration of macroalgae into aquatic feeds remains a challenge as nutritional impacts, processing technologies and bulking of this ingredient are yet to be fully addressed.
Single Cell Proteins	Following extensive years of research, only a limited number of products have emerged, and their availability in the market is quite restricted. These products are very expensive and involve complex production processes. Additionally, the regulatory framework for these products remains undefined. One key informant from the industry operates in this space, but is limited by access to aggregated and sorted waste to grow single cell proteins, and by the relatively high cost of this product when compared to conventional ingredients. They are subsequently moving away from supplying single cell proteins as a feed ingredient and are instead concentrating in manufacturing feed themselves.
Water morning glory (Ipomoea aquatica)	There is no existing product that allows for the use of freshwater plants in their fresh state; they must be dried and ground. Unfortunately, for most there are no apparent nutritional benefits in doing so and the process can be costly. While water morning glory provides some nutritional benefit to fish growth, it is not considered a sufficient product in terms of its protein or fat content.

This has resulted in a list of five alternative and three novel (Table 6), which are further discussed in the following chapters.

Table 6. Final list of ingredients.

Ingredient	Use	Ingredient purpose
Canola meal	Alternative	Protein
Distillers Dried Grains with Solubles (DDGS)	Alternative	Protein
Freshwater shrimp (Caridina nilotica)	Alternative	Protein
Peanut meal	Alternative	Protein/supplement
Sorghum	Alternative	Carbohydrate/energy/binding
Black soldier fly (BSF)	Novel	Protein
Duckweed (Lemna minor)	Novel	Protein, microelements
Yeast from brewer's waste	Novel	Protein, palatability

2.3.1. Technology Readiness Level (TRL)

The suitability of the selected novel and alternate ingredients is assessed based on the Technology Readiness Level (TRL)—a systematic metric to assess the maturity of a particular technology or innovation. It uses a scale to gain understanding of its stage of development and readiness for practical application (NASA, 2023).

The TRL scale ranges from 1 to 9, with each level representing a different stage in the technology development process (Table 7). At the lower end (TRL 1-3), technologies are in the conceptual or experimental phase, often characterised by basic research and lab-scale experiments. As technology progresses through the mid-range (TRL 4-6), it undergoes prototype development, testing, and validation in relevant environments, demonstrating its feasibility and functionality. In the higher TRL levels (7-9), the focus shifts towards finalising the technology for commercialisation, with extensive field testing, integration into operational systems, and optimisation for widespread use.

This approach is used with ingredients to understand how close it is to being commercialised. If an ingredient still needs to be trialled within a feed, and anti-nutritional challenges need to be overcome, it would be at a TRL of 1-3. Once it has been trialled and processing challenges identified, it could move to TRL 4-6 whilst these issues are tackled. If what remains is bringing an ingredient into large-scale commercial usage through aggregation channels to enable bulking, or larger plants to process ingredients then the TRL would fall between 7-9.

Table 7: Technology Readiness Level based on the work by NASA (2023).

Phase	TRL	Ingredient
Research	1	Basic principles
	2	Concept and application formulations
	3	Concept validation
Development	4	Experimental pilot
	5	Demonstration feed pilot
	6	Industrial feed pilot
Deployment	7	First implementation
	8	Some record of implementation
	9	Industrial use

2.4. Modelling tilapia feeds

Tilapia feeds are divided into two main categories: starter feeds and grow-out feeds. Starter feeds typically consist of crumbles sized below 1.5mm, with protein content exceeding 48% and make up around 5% of total feed volumes through the lifecycle. Grow-out feeds come in sizes ranging from 2.0mm to 4.5mm, containing 35% and 30% protein, respectively. The smaller sized, early grow-out feeds account for about 15% of the total quantities, while grow-out feed constitutes approximately 80% of the total feed provided.

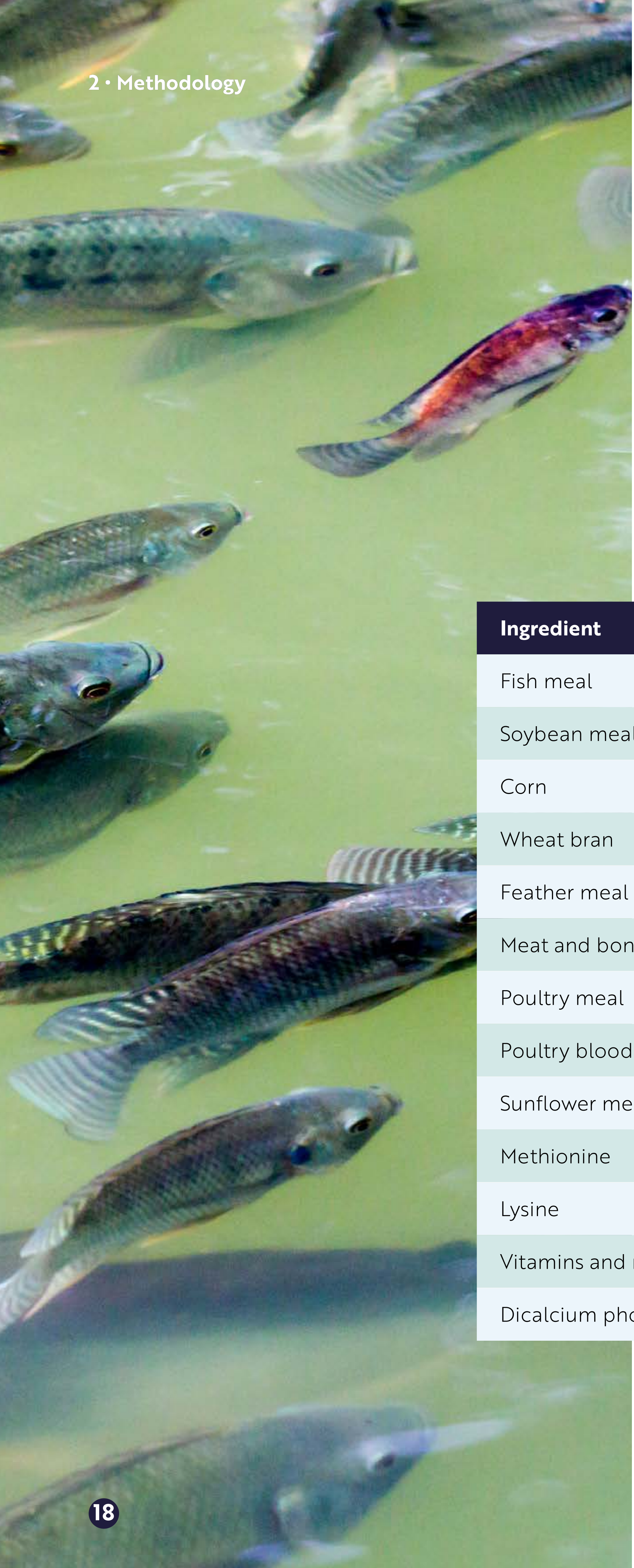
The technical aspects of feed production hold equal importance alongside nutritional considerations. Notably, tilapia feeds are recognised for their floating pellet nature and high-water stability. This stability is crucial to prevent pellet disintegration and nutrient leaching. To meet these requirements, high-quality tilapia feeds are commonly produced using the extrusion process. A key component in the formulation is an ample amount of starch, essential for pellet formation.

2.4.1. Nutritional content

The nutritional composition of various tilapia feeds is detailed in Table 8. These specifications are derived from the "Draft East African Standards – Compounded fish feed – specifications – Part 1: Tilapia and catfish," as well as practical experience (10 years of formulation of fish feeds in EA). It is important to note that the standards permit a broad range of variability in nutritional composition, and in practice, variations exist among different feed producers. The values presented in Table 8 represent intermediate nutritional contents, acknowledging the potential for deviations within the industry.

Table 8. Nutritional composition of three typical tilapia feeds that cover the nutritional needs along the whole production process.

Nutrient	Starter feed (%, as is basis)	Early grow-out feed (2mm)	Grow-out feed (4.5mm)
Protein (%)	48	35	30
Fat (%)	5	5	4
Fibre (%)	<4.0	<5	<6
Ash (%)	<10.0	<10.0	<10.0
Starch (%)	12-22	12-22	12-22
Moisture (%)	8.0	8.0	8.0
Ca (%)	<2.5	<2.5	<2.5
P (%)	0.8-1.2	0.8-1.2	0.8-1.2
Lysine (%)	2.64	1.92	1.65
Methionine + cycteine (%)	1.54	1.12	0.96
Vitamins and minerals premix	Yes	Yes	Depends on culture system



2.4.2. Prices of ingredients

Table 9 displays the prices of the key ingredients utilised in the simulation. These prices have been adjusted to reflect the market rates as of December 2023 and are indicative of the current stock prices at the feed mill.

Table 9. Prices of conventional feed ingredients in EA (Uganda) that are updated to December 2023. Prices are for ingredients sourced by feed mills.

Ingredient	Price (USD/t)
Fish meal	1,800
Soybean meal	670
Corn	335
Wheat bran	190
Feather meal	1,150
Meat and bone meal	720
Poultry meal	1,200
Poultry blood meal	1,210
Sunflower meal	135
Methionine	5,340
Lysine	3,200
Vitamins and minerals premix	11,500
Dicalcium phosphate (DCP)	800

2.4.3. Typical formulations

Based on the prices of conventional ingredients outlined in Table 9 and the nutritional requirements specified in Table 8, a least-cost formulation was conducted using linear programming software (Brill Formulation).

The resulting formulations and their corresponding prices are detailed in Table 10. These formulations serve as the "basic formulas" and form the foundation for the evaluation of alternative and novel ingredients. The guiding principles behind these specific formulations are as follows:

1. A higher protein level in the feed necessitates the use of ingredients from animal origin, characterised by relatively high protein levels and a balanced amino acid profile.
2. The starter feed, being in crumbled form, eliminates the necessity to produce floating pellets. As a result, the starch level can be relatively low.
3. By utilising conventional ingredients, the resulting formulas are well-balanced and encompass all essential nutrients, achieving the most cost-effective price.

Table 10. Formulation of three typical feeds for tilapia and the resulting price of the ingredient mix. These formulas are termed "basic formulation".

Nutrient	Starter feed (%, as is basis)	Early grow-out feed (2mm)	Grow-out feed (4.5mm)
Fish meal	10.0	-	-
Soybean meal	9.9	25.0	20.9
Corn	15.0	31.3	31.6
Wheat bran	10.0	10.0	15
Feather meal	9.9	0	0
Meat and bone meal	9.6	14.7	15
Poultry meal	15.0	14.0	4.6
Poultry blood meal	10.0	2.0	2.0
Sunflower meal	10.0	2.3	10.0
Methionine	0.1	0.15	0.2
Lysine	0.1	0.15	0.5
Vitamins and minerals premix	0.4	0.4	0.3
Dicalcium phosphate (DCP)	0	0	0
Price (USD/t)	854.0	635	527.0

3. Potential Ingredients

The following section delves into future raw materials with the potential to serve as ingredients for aquafeeds. This chapter is structured into two categories: "alternative ingredients", which evaluates raw materials utilised worldwide in aquafeeds but not in EA; and "novel ingredients", which scrutinises raw materials seldom employed as ingredients anywhere globally, but with relevance to EA and having potential as sustainable ingredients for aquafeeds in the region.

3.1. Alternative ingredients

The alternative ingredients are those commonly utilised in aquafeeds globally but are currently absent in EA. Expanding the array of ingredient options within the aquafeed industry is imperative as it helps to diminish reliance on the currently available but limited conventional ingredients in the region, while reducing imports.

This section evaluates selected alternative ingredients, deemed suitable for tilapia feed formulation and possessing significant potential to emerge as commercial raw materials for tilapia feeds in EA. This evaluation encompasses scrutiny of nutritional adequacy, market competition, pricing dynamics, and logistical challenges. Addressing these hurdles is paramount to establishing these alternatives as viable options amidst competing ingredients.

The reasons for the non-utilisation of these "alternative ingredients" in EA likely stem from commercial or logistical obstacles rather than nutritional or technical challenges. Hence, to assess the feasibility of incorporating these ingredients into aquafeeds, we modelled their cost-effectiveness at estimated market prices.

Table 11 presents a compilation of alternative ingredients that, based on our assessment, possess the highest potential for commercial integration into aquafeeds in EA. Table 12 presents the nutritional profiles of these ingredients. Canola meal and DDGS are genuine alternative ingredients extensively employed in aquafeeds, yet sourcing them necessitates importation as they are locally unavailable. Peanut meal and sorghum, though locally abundant, are underutilised in EA and scarcely employed elsewhere in aquafeed production. Freshwater shrimp, a local resource exclusive to EA, remains conspicuously absent in aquafeeds within the region.

Table 11. Selected alternative ingredients

Ingredient	Ingredient purpose	Source
Canola meal	Protein	Imported
Distillers Dried Grains with Solubles (DDGS) from corn	Protein	Imported
Peanut meal	Protein/energy	Local
Sorghum	Carbohydrate/energy/binding	Local
Freshwater shrimp meal	Protein, palatability, health	Local

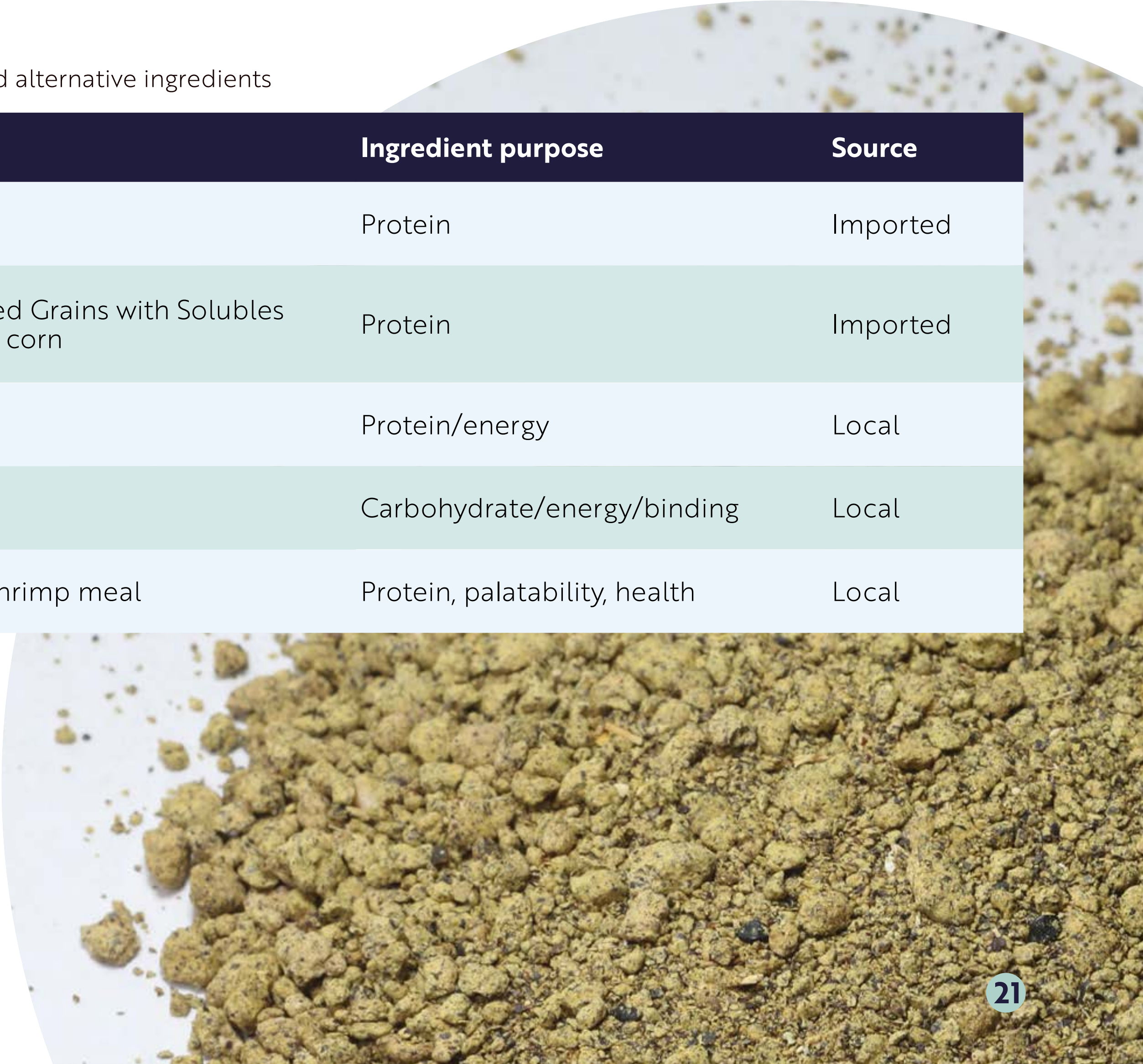
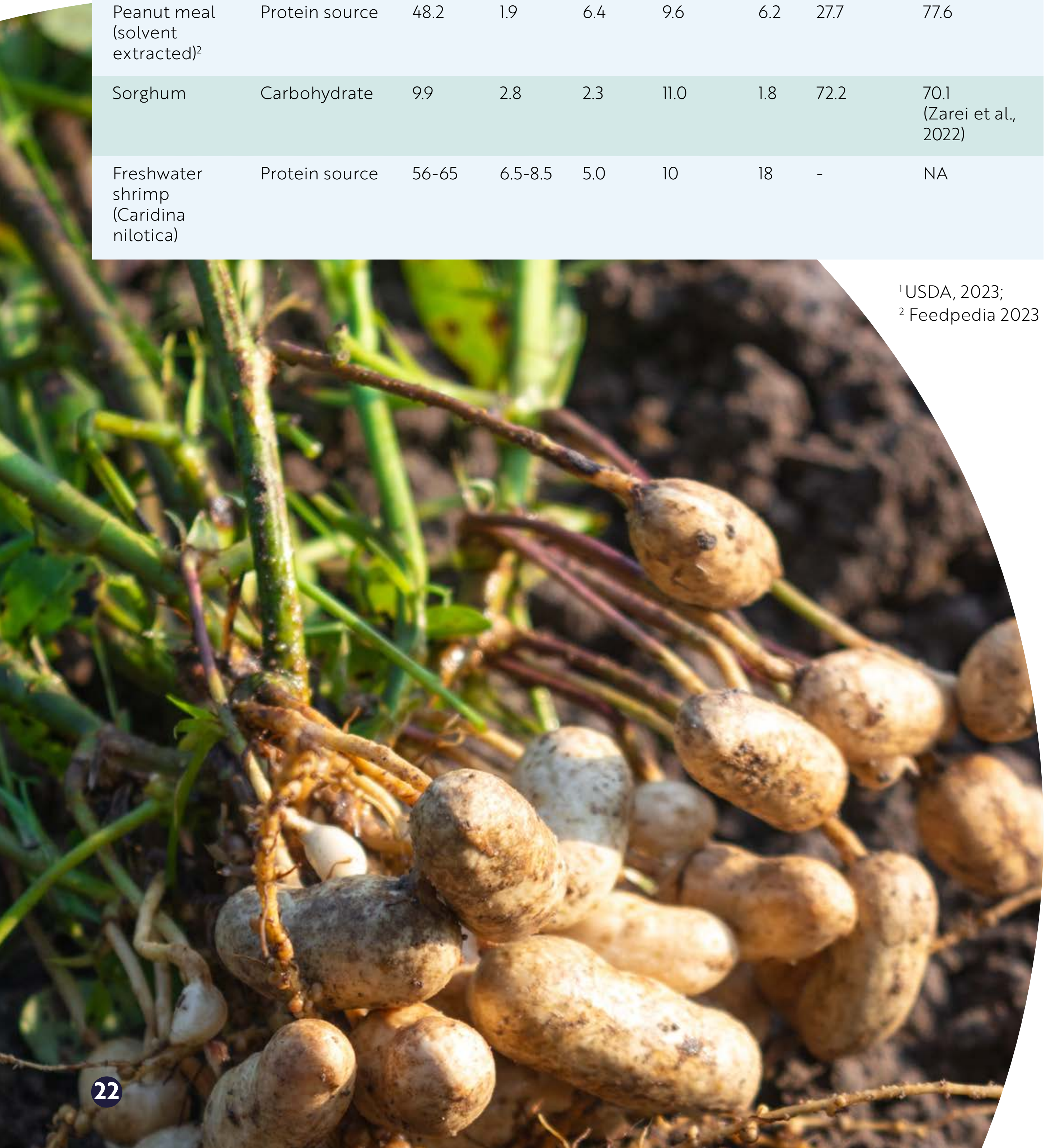
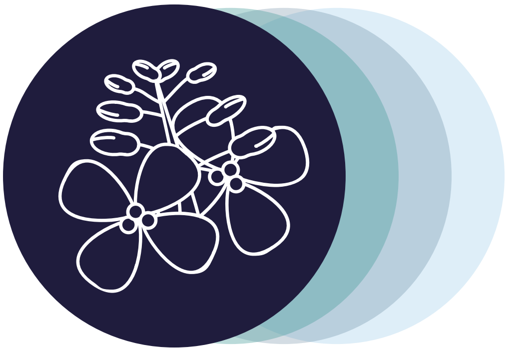


Table 12. Nutritional content of alternative ingredients for tilapia feeds. All values are on an "as is" basis. The carbohydrate level is based on calculations. Digestibility refers to the digestibility of the main ingredient.

Ingredient	Category	Crude protein (%)	Crude fat (%)	Crude fibre (%)	Moisture (%)	Ash (%)	Carbohy-drate (%)	Digestibility (%)
Canola meal (COPA, 2019)	Protein source	36.0	2.8	12.0	12	6.4	30.8	85.0 (Sklan et al., 2004)
Distillers Dried Grains with Soluble (DDGS)[1]	Protein source	28.0	10.0	10.0	9.0	5.2	37.8	NA
Peanut meal (solvent extracted)[2]	Protein source	48.2	1.9	6.4	9.6	6.2	27.7	77.6
Sorghum	Carbohydrate	9.9	2.8	2.3	11.0	1.8	72.2	70.1 (Zarei et al., 2022)
Freshwater shrimp (Caridina nilotica)	Protein source	56-65	6.5-8.5	5.0	10	18	-	NA

[1] USDA, 2023;
[2] Feedpedia 2023





3.1.1. Canola

Canola meal is widely utilised as a protein source in aquafeeds across the globe. Canola meal is a by-product of the oil extraction process from rapeseed (Brassica napus and Brassica campestris/rapa). The term "canola" was coined to differentiate it from traditional rapeseed, as it was specifically bred to reduce the levels of undesirable erucic acid and glucosinolates. With the changes made to canola production and processing, canola meal is now a palatable source of protein for aquafeeds.

3.1.1.1. Nutrition and quality considerations

Typically, canola contains approximately 36% protein (Table 22), with relatively high apparent digestibility. It has a low fat content but is characterised by a relatively high level of crude fibre, which could potentially limit its use in tilapia feeds.

Canola meal contains small amounts of heat-labile (glucosinolates at 3.2 μmol/g) and heat-stable (phytic acid, phenolic compounds, tannins, saponins and fibre) antinutritional factors, but for pelleted aquafeed production this factor is not limiting. The rest of the antinutritional factors in canola meal are typical to most plant materials and limit the use of canola to 10-15% in tilapia feeds. Historically, the inclusion level of canola meal was limited by the bitterness and toxicity of glucosinolates. However, recent advances have significantly reduced the levels of glucosinolates in canola meal and there are no more restrictions on its use.

Image: Sergei S. Scurfield

3.1.1.2. Supply

In 2022, global annual production of rapeseed and canola was about 90 million tons, with the most dominant producers being (in order of quantities) the European Union, Canada, China, India, and Australia (USDA, 2023). Canola and rapeseed meals are the second most widely traded protein ingredients after soybean meal, with all year-round availability. Canola and rapeseed meals are commonly used as an ingredient in animal feeds, including aquafeeds.

Canola meal is not produced in any of the EA countries, and to the best of our knowledge, it is currently not imported to EA. Consequently, this ingredient is currently unavailable for aquafeeds in the region but does have potential in extruded pellet production.

3.1.1.3. Cost and production

The price of canola meal ranges between 350-400 USD/t for 36% protein product (Tridge, 2023). Canola meal is usually sold in bulk, shipping thousands of tons; meaning that purchase of this ingredient would likely be carried out by importers who would distribute to feed mills. Purchase of individual bags is possible, but the price is higher.

There are no known technical limitations that could restrict the utilisation of canola meal, either in extrusion or steam pelleting processes. There are no regulatory restrictions in importing canola meal into EA countries, provided that the meal complies with the phytosanitary regulations.

3.1.1.4. Reference to use in tilapia feeds

Tilapia exhibit a high protein apparent digestibility of 85% when fed with canola meal, which is only slightly lower than the digestibility for fishmeal. Moreover, the essential amino acid profile of canola meal is well-balanced and aligns with the nutritional requirements of fish, with lysine being the limiting amino acid.

The incorporation of canola meal into tilapia feeds is substantiated by a body of scientific evidence. A study conducted by Zhou and Yue (2010) demonstrated that dietary inclusion levels of up to 19% had no detrimental impact on the growth and feed utilisation efficiency of tilapia.

3.1.1.5. Least cost formulation

Modelling canola meal in the formulation of the three feeds, at 458 USD/t (Feed mill in stock prices). The results are shown in Table 13.

The economic contribution of canola meal to the two grow-out feeds is minimal, and it is not included in the starter feed unless its shadow price, set at 490 USD/t, is reached. Canola meal may be more prominently utilised if issues arise over the availability or price increase of other protein-providing ingredients.

Table 13: Adding canola meal at a price of 458 USD/t to three tilapia feed formulations. The nutritional composition of all feeds was kept constant, regardless of ingredient composition.

Nutrient	Starter feed (%, as is basis)	Early grow-out feed (2mm)	Grow-out feed (4.5mm)
Canola meal	-	3.9	7.7
Fish meal (%)	-	-	-
Soybean meal (%)	-	25.0	15.1
Corn (%)	-	28.8	29.5
Wheat bran (%)	-	8.6	15.0
Feather meal (%)	-	-	-
Meat and bone meal (%)	-	14.2	15.0
Poultry meal (%)	-	15.0	4.7
Poultry blood meal (%)	-	-	2.0
Sunflower meal (%)	-	3.7	10.0
Methionine (%)	-	0.15	0.2
Lysine (%)	-	0.25	0.5
Vitamins and minerals premix (%)	-	0.4	0.3
DCP (%)	-	-	-
Price (USD/t)	-	634.3	525.5

3.1.2. Distiller's dried grains with solubles

Distiller's dried grains with solubles (DDGS) is a dried by-product that remains after the fermentation of grain (corn, wheat, sorghum and barley) mash by selected yeasts and enzymes to produce ethanol and carbon dioxide. In this report only DDGS resulting from corn fermentation will be discussed, as it is the most common DDGS commodity globally. DDGS is used in terrestrial animal feeds, as well as in aquafeeds. It is added to tilapia feeds as a cost-effective protein and energy source.

3.1.2.1. Nutrition and quality considerations

The protein content of DDGS is relatively low (compared to soybean meal) and accordingly the contribution of essential amino acids (EAA) is relatively low (Table 22). Expressed as a percentage of crude protein, DDGS is deficient in several essential amino acids, including lysine, threonine, tryptophan, arginine, isoleucine and phenylalanine, relative to soybean meal. Comparing the essential amino acid content of DDGS to the requirements of Nile tilapia, DDGS is severely deficient in lysine and to a lesser extent in methionine (NRC, 2011). To the best of our knowledge the apparent protein digestibility of DDGS by tilapia has not yet been tested.

Corn DDGS contains yellow pigments (xanthophylls) at a level of 15–25 ppm (Lim et al., 2011). These xanthophylls (mainly lutein, zeaxanthin and b-cryptoxanthin) might impart yellow pigment in fish skin and flesh (as shown for other fish species). Enhancing fish skin colour might be an advantage as the fish appears more attractive. No studies have been conducted on the effect of dietary levels of xanthophylls on tilapia fillet pigmentation.

3.1.2.2. Supply

Most global DDGS is produced in the United States (85%), at a total amount of 44 million tonne/yr (US Grain Council 2023). Other producing countries are the Netherlands (about 3.6% of global production), Belgium (1.5%) and Canada (1.3%) (Tridge, 2023). DDGS is used in terrestrial animal feeds, as well as in aquafeeds.

3.1.2.3. Cost and production

DDGS are traded globally, mainly in bulk shipping. The indicative price on Free On Board (Incoterms) basis is 290 USD/t (November 2023, Tridge 2023) and the price in the feed mills is expected to be 458 USD/t, when transportation and importation costs (estimated values) are added. The product is available all year round without any seasonality and to the best of our knowledge it is not yet available in EA countries.

3.1.2.4. Reference for use in tilapia feeds

DDGS is relatively palatable to fish, including tilapia. The inclusion of DDGS in the diet has been shown to increase feed intake in Nile tilapia (Lim et al., 2007). An increased fat level and the presence of distiller's solubles in diets containing DDGS might be responsible for these beneficial effects (Li et al., 2010). Corn DDGS contains approximately 10% corn oil (Table 22), which is a highly digestible energy source. It also contains approximately 58% linoleic acid (18:2n-6), an essential fatty acid for tilapia (NRC 2011).

High crude fibre and low protein content may limit the use of DDGS in tilapia feeds, although tilapia, being an omnivorous fish, can tolerate relatively high levels of fibre. Antibiotics, such as penicillin, virginiamycin, erythromycin and tylosin (tetracycline), might be used in the process of DDGS production to control the growth of bacteria during the fermentation process. The major concern is that these antibiotic residues might end up in animal feeds and potentially in fish tissues used for human consumption (Lim et al., 2010). Nevertheless, nowadays it is possible to source DDGS that is guaranteed to be antibiotic free.

Although the use of DDGS in tilapia feeds is relatively new (about three decades), to date there is a large amount of scientific reference to the use of DDGS in tilapia feeds. For example, Lim et al (2010) tested different inclusion levels of DDGS in tilapia feeds and concluded that inclusion levels of up to 20% had no negative effect on various culture parameters, compared to control.

3.1.2.5. Least cost formulation

DDGS was included in the formulation of the three feeds, at a price of 458 USD/t (feed mill in stock prices). The results are shown in Table 14.

As illustrated, at the price of 458 USD/t, DDGS is excluded from starter feeds. It only becomes part of the formulation when its shadow price of approximately 370 USD/t is reached. Given that starter feeds for tilapia are akin to feeds for predatory fish, there is no discernible nutritional advantage in incorporating this ingredient into this particular product.

In early grow-out and grow-out feeds, DDGS can be reasonably included at levels around 10%. At this inclusion rate, the cost reduction for early grow-out and grow-out feeds is 6 and 8.4 USD/t, respectively. While the reduction in price (approximately 1-2% of the total feed price) may not be deemed highly significant, it can play a crucial role in diversifying the pool of raw materials in the feed mill. This in turn helps mitigate issues related to the availability and the ever-fluctuating prices of the various raw materials in the feed mill.

Table 14. Adding DDGS at price of 458 USD/t to three tilapia feed formulations. The nutritional composition of all feeds was kept constant regardless of ingredient composition.

Nutrient	Starter feed (%, as is basis)	Early grow-out feed (2mm)	Grow-out feed (4.5mm)
DDGS	-	8.4	11.8
Fish meal (%)	-	-	-
Soybean meal (%)	-	25.0	17.3
Corn (%)	-	28.0	26.9
Wheat bran (%)	-	10.0	15.0
Feather meal (%)	-	-	-
Meat and bone meal (%)	-	15	12.7
Poultry meal (%)	-	9.0	-
Poultry blood meal (%)	-	3.9	5.3
Sunflower meal (%)	-		10.0
Methionine (%)	-	0.15	0.2
Lysine (%)	-	0.15	0.5
Vitamins and minerals premix (%)	-	0.4	0.3
DCP (%)	-	-	-
Price (USD/t)	-	629.0	516.0

3.1.3. Peanut meal

Peanut or groundnut (Arachis hypogaea) meal (PM) emerges as the by-product resulting from the extraction of oil from peanut seeds. PM is generated through mechanical extraction methods, primarily using expeller processes, and occasionally through a combination of mechanical and solvent extraction.

3.1.3.1. Nutrition and quality considerations

Peanut meal serves as a protein-rich ingredient widely utilised in feeding various classes of livestock, including fish. The nutritional composition of PM (Table 12) exhibits variability depending on the production process and oil extrusion method. Additionally, the composition may be influenced by the inclusion of shells and peanut skin along with the seeds before oil extraction. Peanut meal boasts a high protein content, ranging from 45-50%, comparable to soybean meal. Notably, the essential amino acid profile in PM moderately aligns with most fish nutritional requirements: with relatively lower levels of lysine, methionine, and tryptophan. Conversely, PM is a rich source of arginine, although this amino acid is generally not a limiting factor in fish nutrition. Protein digestibility appears variable, reaching 86.4% in barramundi fish (Vo et al., 2020) but only 77.6% in tilapia fish (Zhou and Yue, 2012).

Due to the diverse range of extraction processes, the oil content in peanut meal varies significantly, ranging from less than 3% for solvent-extracted meals to 9% for mechanically extracted meals. The fatty acid composition of peanut meal predominantly includes oleic acid (C18:1) at 56.3%, linoleic acid (C18:2) at 21.3%, and palmitic acid (C16:0) at 12.3%; together these three acids constitute 90% of the fatty acids in peanut oil (Valencaa et al., 2020). With this fatty acid profile, PM can be considered a valuable source of essential fatty acids for tilapia, despite its relatively low levels of linolenic acid (18:3).

The carbohydrate fraction in peanut meal is approximately 25%, with the majority being starch. While the starch level is not high, it may contribute to the binding properties of extruded pellets. The typical crude fibre level is 6.4%, higher than that in high-quality plant materials like soybean meal. In some products, peanut meal may include up to 10% fibre if it contains a significant amount of skin and shell fragments.

Like other legume seeds, peanuts contain anti-nutritional factors, such as tannins, lectins, and trypsin inhibitors (Jithender et al., 2019, Feedipedia). The presence of anti-nutritional factors in peanut meal is influenced by the inclusion of hulls and seed coats, with higher inclusion leading to more anti-nutritional factors . Peanut lectins can be fully inactivated by heat, making peanut products safe for animal feeding under regular processing conditions.

One major obstacle in using peanut meal for animal nutrition is the frequent contamination with aflatoxin (List, 2016), produced by fungi such as Aspergillus flavus and Aspergillus parasiticus. Aflatoxin contamination can occur throughout the value chain (Njoroge, 2018), primarily due to poor storage conditions in humid and hot climates. Aflatoxin is highly toxic to all animals, including fish, and has led to acute mortalities in tilapia even at low concentrations of 80 ppm in the feed (NRC, 2011).

3.1.3.2. Supply

The peanut stands out as one of the five most important oilseeds globally. Its cultivation spans six continents, contributing to a total global production of approximately 54 MMT in 2021. EA alone contributes around 900 TMT, with Tanzania leading as the primary producer, followed by Uganda (FAOSTAT, 2024). Notably, 48% of peanut production in EA is dedicated to oil extraction (USDA, 2023), indicating potential volumes of peanut meal already available as a feed ingredient.

Groundnuts are typically planted in EA at the onset of the rainy season, which usually occurs from March to May or from September to November, depending on the specific location. As a result, peanut meal is not readily available throughout the year but mainly after the two harvest times. The prevalence of mycotoxin contamination restricts the storage time of this ingredient, making it rarely found out of season.

3.1.3.3. Cost and production

The estimated cost of a peanut meal is $483 USD per ton. Since it is produced locally in EA, it is less sensitive to price fluctuations related to logistics. Prices may also be affected by the quality of the product, primarily due to safety and cleanliness from mycotoxins. Products that are guaranteed to be thoroughly cleaned may be priced higher.

Efforts to reduce aflatoxins in peanut products involve improved pre-harvest, post-harvest, and storage practices, resistant peanut cultivars, biological control agents, and detoxification methods.

Aqueous ammonia has been effective in detoxification of aflatoxin but requires strict safety regulations. Other detoxification processes, like using hydrogen peroxide, formaldehyde, and calcium hydroxide, are effective but complicate the use of peanut meal and increase product prices.

There is no evidence of any significant effect of peanut meal on the production process, especially when expected inclusion levels are low. This caution in inclusion is due to the potential danger of mycotoxin poisoning in feed.

3.1.3.4. Reference for use in tilapia feeds

Only a handful of studies have tested the use of peanut meal in tilapia feeds and they indicate relatively poor growth rates, and the maximum inclusion rate without negative effects on growth is around 15% of the total feed (da Silva et al., 2017). The poor growth is attributed to an imbalanced essential amino acid profile, particularly low levels of lysine and methionine.

Due to the toxicity and prevalence of aflatoxin contamination, most countries adhere to a maximum allowed limit of 20 ppb, following EU regulations (Commission directive, 2003/100/EC). This stringent limit restricts its use in fish feed, with many nutritionists preferring not to include it, or limiting it to a maximum of 5% inclusion rate (personal information).

3.1.3.5. Least-cost formulation

Modelling of the incorporation of peanut meal into tilapia feeds reveals that at 483 USD/t, it is feasible to include it only in the grow-out feed and therefore the other two feeds are not shown. At this price, the model included peanut meal at a level of 0.9% (Table 15). The low inclusion level, approximately 1%, indicates that the current price is near the shadow price. To include peanut meal into the starter and early grow-out feeds, the price of this ingredient should be 450 and 410 USD/t, respectively.

Table 15: Adding peanut meal at price of 483 USD/t to grow out tilapia feed formulation. The nutritional composition of all feeds was kept constant regardless of ingredient composition.

Nutrient	Grow-out feed (4.5mm)
Peanut meal	0.9
Fish meal (%)	-
Soybean meal (%)	19.8
Corn (%)	31.6
Wheat bran (%)	15.0
Feather meal (%)	-
Meat and bone meal (%)	15.0
Poultry meal (%)	4.7
Poultry blood meal (%)	2.0
Sunflower meal (%)	10.0
Methionine (%)	0.2
Lysine (%)	0.5
Vitamins and minerals premix (%)	0.3
DCP (%)	-
Price (USD/t)	526

In summary, peanut meal contains a relatively high level of protein of intermediate quality and a high-quality lipid fraction. It contains relatively low levels of ANFs and those present are considered to be less harmful relative to those in other legumes. However, the high risk of aflatoxin contamination limits its use in fish feeds. There is insufficient research on peanut meal in tilapia feeds, and more studies are needed to address the amino acid imbalance and explore its potential in fish nutrition.

3.1.4. Sorghum

Sorghum is a drought-resistant cereal grain typically cultivated in semi-arid conditions. Worldwide sorghum has been ranked the fifth most important cereal grain after wheat, maize, rice and barley, in terms of both production and area planted (Zarei et al, 2022).

3.1.4.1. Nutrition and quality considerations

Sorghum has a rich source of carbohydrates (Table 12) and is primarily used in aquafeeds as a contributor of starch for the extrusion process and as an energy source.

Sorghum crops are categorised based on their use, such as for forage or grain. Grain sorghums are classified into three types according to their tannin contents: type I, that is tannins free while type II and III contain low and high levels of tannin, respectively (Zarei et al., 2022). In addition, varietals are also grouped according to grain colour, e.g., black, brown, red, yellow, and white (Annex 3). Sorghum grain colour is indicative of several attributes, including nutrient level and ANF concentration (such as phenolic compounds and tannins). Red, orange, and bronze are the most commonly raised varieties and mostly used for animal feed. All sorghum varieties are the result of conventional selective breeding and therefore are all GMO free (Zarei et al., 2022).

The digestibility of the starch in sorghum is considered to be low, relatively to that of wheat and corn (Zarei et al, 2022). This might be explained as the

starch in sorghum is bound in a protein matrix that limits the activity of digestive enzymes. Nevertheless, Sklan et al. (2004) found the carbohydrate digestibility of sorghum by tilapia was 70.1%, which is comparable to that of wheat (71.7%) and superior over the carbohydrate digestibility of corn (57.9%). The discrepancies between the results of different research might be explained by testing different sorghum varieties and probably because of different feed production methods.

Sorghum's protein content falls between that of wheat and corn. Its amino acid composition varies with its protein content. Research has confirmed that sorghum grains contain relatively low levels of EAAs crucial for aquafeeds, including lysine, threonine, and total sulphur amino acids. The levels of these EAAs in sorghum are comparable to those in corn, with, for instance, lysine present at 0.2% in sorghum and 0.25% in corn (McCuistion et al., 2019). Since sorghum is primarily included in aquafeed formulations for its starch content, the practical significance of its amino acid composition in feed formulation is relatively limited. Furthermore, the total apparent digestibility of sorghum grain proteins is measured at 85.5%, surpassing corn proteins with an apparent protein digestibility of 75.1% (McCuistion et al., 2019).

Sorghum grains have relatively low oil content, typically 2-3%. The fatty acid composition of sorghum oil is linoleic acid at 52%, oleic acid at 32%, palmitic acid at 10%, stearic acid at 4%, and linolenic acid at 1% (Zarei et al., 2022). Given the limited total oil content in sorghum grains, its contribution to the dietary balance of essential fatty acids and energy in the feed is practically negligible.

3.1.4.2. Supply

World production of sorghum (2022) was 55 million tons. The main producers are Nigeria with 6.7 MMT/y, Sudan with 5.2 MMT/y, Mexico with 4.9 MMT/y, United states with 4.8 MMT/y and Ethiopia with 4.2 MMT/y (USDA, 2023b). Sorghum cultivation is mainly practised in developing countries with 90 per cent of the cultivated area being in African and Asian countries. Africa is the largest producer of sorghum accounting for one-third of global production. In EA, Tanzania is the leading producer of sorghum, followed by Uganda, Rwanda and Kenya (Table 16). Uganda, Kenya and Rwanda produce over 500,000 tonnes (Table 16), 90% of which is accessible locally.

Table 16. Land area and productivity of sorghum in EA

Country	Kenya	Rwanda	Tanzania	Uganda	EA (totals)
Harvested Area (ha)	197,403	166,669	1,035,257	228,855	1,628,184
Production (tonnes)	135,000	178,370	1,077,000	200,000	1,590,370
Yield (t/ha)	0.68	1.07	1.04	0.87	0.98

Given its range of uses, research on sorghum focuses on improving yield, resistance to pests and diseases, and nutritional content. These advancements contribute to sustainable agriculture in the region. In EA, sorghum is used for food, feed and malting or brewing (IFAD, 2018), but rarely included in livestock feed rations. About 85-88% of the sorghum production is directly consumed by humans (Tanwar et al., 2023; Orr et al., 2002).

3.1.4.3. Cost and production

The cost of Sorghum is about 370 USD/t (EA Regional Sorghum Supply and Market Outlook, MarMugo-Bundich 2023). In November 2023 it was slightly more expensive than maize, which was offered at a price of 335 USD/t.

Technically, sorghum, as any other carbohydrate source, is used as a binder for pellet formation in the extrusion process. The starch gelatinisation temperature of sorghum is 68-76°C, which is higher than that of corn and wheat; meaning that extrusion of sorghum containing feeds must be carried out in higher cooking temperatures, consuming more energy during the feed production process. Moreover, it has been claimed that pellets that contain sorghum in their formulation do not bind as well as pellets that contain maize (Feedipedia, 2023).

3.1.4.4. Reference for use in tilapia feeds

Like other plant material, sorghum grains contain several anti-nutritional factors. Sorghum grain might contain trypsin and amylase inhibitors, phenolic compounds, phytic acid, and tannins. These compounds are known to have a negative impact on protein, carbohydrate, and mineral metabolism in fish (Zarei et al., 2022). Tannins are the most potent ANF in sorghum, but as discussed previously, its concentration is related to sorghum variety and culture condition; therefore, varieties with low amounts of ANF's can be sourced by feed millers.

Studies reporting the dietary effect of sorghum in tilapia feeds are inconclusive. There are very few studies testing the effect of sorghum on growth parameters of tilapia. Al-Ogaily et al. tested the growth performance of tilapia Oreochromis niloticus (L.) which were fed diets containing different grain sources (maize, wheat, barley, sorghum and rice) at a level of 25%. Fish fed the diet containing sorghum had the highest weight gain, highest specific growth rate and the best feed conversion ratio (Al-Ogaily et al., 1996).

3.1.4.5. Least cost formulation

Sorghum has been evaluated in the formulation of all three feeds at a price of 370 USD/t (Feed mill in-stock prices). However, at this price, sorghum is not included in any of the three formulas. In the early grow-out feed, the shadow price of sorghum is 280 USD/t, while in the grow-out feed, it is 315 USD/t, nearly equal to the price of corn. In the starter feed, sorghum is not included at any price due to its low-fat content. In grow-out feeds, sorghum can serve as an alternative to corn in case the price of corn increases, provided sorghum remains at a stable price level.

In conclusion, sorghum is well-suited for sustainable agriculture. It is drought-tolerant and thrives in a variety of climates, requiring fewer resources such as water and fertilisers and is less prone to fungal infections and mycotoxin contamination (Agriculture, 2022). This aligns with the growing emphasis on eco-friendly and resource-efficient fish farming practices. The existing data supports the safe utilisation of sorghum in tilapia feeds, allowing for up to 25% inclusion in the formula. When the market price is competitive, sorghum can be a viable and competitive alternative to traditional grains in aquafeed, such as wheat and corn.

3.1.5. Freshwater shrimp

The freshwater shrimp (local name ochonga; Latin name Caridina nilotica (Roux)) is an atyid shrimp typically found in benthic habitats and amongst aquatic weeds; it grows to a length of about 25mm.

3.1.5.1. Nutrition and quality considerations

Freshwater shrimp meal serves primarily as a protein source while also enhancing palatability and providing a natural supply of micronutrients such as carotenoids and minerals. The nutritional composition of freshwater shrimp (FWS) is outlined in Table 12, presenting it as a viable protein source for aquafeeds. Table 17 provides a comparative analysis of the amino acid profiles of freshwater shrimp and fish meal (FM) derived from Rastrineobola argentea. Two profiles are presented: the first represents the percentage of amino acids (AA) relative to total meals, while the second is the percentage of each AA from total protein. This calculation facilitates a meaningful comparison between the two ingredients, considering their differing protein levels.

The amino acids profile as a percentage of protein underscores that both freshwater shrimp and fish meal boast considerable levels of essential amino acids crucial for aquafeed formulation, particularly lysine and methionine. In direct comparison, fish meal surpasses freshwater shrimp in the concentration of these two amino acids, whereas freshwater shrimp excels in threonine content compared to fish meal. These findings suggest that freshwater shrimp serves as a suitable source of essential amino acids, with a relatively balanced profile, making it a potential ingredient for tilapia feeds.

Table 17: Amino acid (AA) profile of fish meal (FM) from Rastrineobola argentea and shrimp meal made of C. nilotica (Mugo-Bundi et al., 2013). All values are on "as is basis".

Essential amino acid (EAA)	% of AA in fish meal	% of AA from shrimp meal	% AA from protein in fish meal	% AA from protein in shrimp meal
Arginine	6.01	4.42	8.96	7.88
Histidine	1.7	1.41	2.53	2.51
Isoleucine	4.01	3.61	5.98	6.43
Leucine	6.52	5.71	9.72	10.18
Lysine	5.45	3.51	8.12	6.26
Methionine + Cystine	4.59	2.45	6.84	4.37
Phenylalanine + Tyrosine	6.73	3.79	10.03	6.76
Threonine	3.53	3.41	5.26	6.08
Tryptophan	1.82	1.52	2.71	2.71
Valine	4.07	4.08	6.07	7.27

Shrimp meals are characterised by elevated levels of chitin, a constituent of the shrimp shell, accounting for approximately 10% of its composition (Islam et al., 2016). However, the digestibility of chitin in many fish species, including tilapia, is notably low due to the limited activity of chitinases in the fish digestive tract (Lindsay et al., 1984). In laboratory assessments, typically employing the Kjeldahl method, chitin is detected within the protein fraction. This inclusion artificially raises the Non-Protein Nitrogen (NPN) fraction, introducing a bias in the actual protein level of the meal by indicating a higher protein content than the true value. It is estimated that chitin constitutes around 2-3% of the protein fraction in crustacean meal.

The nutritional quality of freshwater shrimp suffers due to inadequate treatment of shrimp from fishing to processing, compounded by the sun-drying method, potentially leading to decreased product quality, further exacerbated by oil oxidation.

Shrimp are highly susceptible to deterioration, triggering autolysis immediately post-capture, which generates toxic biogenic amines. Prolonged, uncontrolled sun-drying without antioxidants may accelerate shrimp oil oxidation, resulting in rancidity. These detrimental processes significantly compromise product quality, underscoring the importance of employing proper machinery in animal by-product processing to address these challenges.

3.1.5.2. Supply

C. nilotica is the only shrimp inhabiting Lake Victoria, constituting 10% bycatch of the Rastrineobola argentea fishery (Kubiriza et al., 2016). On the Ugandan side of Lake Victoria, the annual catch of R. argentea is about 120,000 tonnes of fresh fish (Kubiriza et al., 2016), suggesting that about 12,000 tonnes of fresh shrimp may be collected annually. Assuming shrimp water content of 75%, the estimated amount of dry shrimp may be about 4,200 tonnes per year (assuming 10% moisture in shrimp meal). Overall, about 17,500 tonnes of freshwater shrimp (based on 50,000 tonnes of fresh catch) could be accessed for fish feed production from the estimated 500,000 tonnes of R. argentea landed from the whole of Lake Victoria annually (Kubiriza et al., 2016).

Ochonga shrimp meal (OSM) is exclusively produced in EA countries and remains confined within this regional boundary, with no cross-border trade. The commonly used fishmeal in EA comes from a common source containing both fish and shrimp that undergoes a sun-drying process and is manually separated post-drying (Kubiriza et al., 2016). Notably, the production of ochonga shrimp meal lacks industrialisation, leading to potential variations in quality and nutritional composition among different batches, production locations, and seasons. The freshwater shrimp supply is not consistent as the fishing depends on various factors, such as weather and governmental fishing bans (Mungiti, 2021).

Interestingly, there has been a substantial increase in the abundance of C. nilotica in the waters of Lake Victoria since 1986, with hydroacoustic surveys projecting an average shrimp biomass of about 22,694 metric tons for the entire lake (Getabu et al., 2003).

3.1.5.3. Cost and production

The price of freshwater shrimp has been calculated from the price of fresh shrimp that is 595 USD/t. Assuming mass loss due to drying and adding 20% for labour and margins, the calculated price of the freshwater shrimp meal should be around 1780 USD/t.

Significant amounts of freshwater shrimp are discarded during processing due to the predominant focus on silver cyprinid. Therefore, potential investors in the feed sector should explore the development and implementation of suitable harvesting and processing protocols.

There is no evidence of any effect of shrimp meal on feed production technology or setup. This is especially when potential inclusion levels are expected to be relatively low, typically less than 10% of total formulation.

3.1.5.4. Reference for use in tilapia feeds

Notably, there is a lack of studies that have examined the protein digestibility of ochonga shrimp meal by tilapia in existing literature. Nevertheless, drawing parallels with the high protein digestibility of krill meal, it is reasonable to infer that its digestibility is similarly elevated.

Several studies have examined the incorporation of ochonga shrimp meal in tilapia feeds. Two studies, which investigated inclusion levels of up to 27% in the total formulation, suggested that freshwater shrimp could serve as a partial substitute for silver cyprinid fishmeal in Nile tilapia feeds in EA (Kubiriza et al., 2016, Mugo-Bundi et al., 2013). These studies indicated no significant impact on tilapia growth at inclusion levels up to 13%. However, when silver cyprinid fishmeal was entirely replaced by freshwater shrimp, tilapia growth decreased, and feed conversion ratio increased. This suggests that freshwater shrimp may be suitable for inclusion in tilapia diets at levels of up to about 10% .

It has been proposed that shrimp meal serves a dual purpose as a feed attractant and palatability enhancer. In efforts to reduce tilapia feed costs, there is extensive reliance on plant-based ingredients, a practice that inadvertently diminishes palatability. Incorporating palatability enhancers like krill meal, a type of shrimp meal, has been shown to enhance feed palatability, leading to improved feeding rates and, consequently, enhanced fish growth rates (Gaber, 2005). These findings suggest that ochonga shrimp meal may not only function as a protein source, but also serve as a valuable functional additive. This is particularly significant considering the potentially high cost of ochonga shrimp meal as a macro ingredient in tilapia feed. However, its economic justification becomes apparent when viewed as an additive that promotes overall feed quality.

3.1.5.5. Least cost formulation

Freshwater shrimp meal is relatively expensive, and from a cost perspective, it cannot be included in the formulation of early grow-out and grow-out feeds, unless deliberately chosen (therefore these two feeds are not shown in table 18). However, in the starter feed, if shrimp meal is substituted for fish meal, as indicated in Table 18, the price of the formula would remain almost unchanged, with only a slight increase of 3 USD/t. Therefore, shrimp meal can serve as a viable partial replacement for imported ingredients (such as fishmeal) with a locally produced raw material, making it a reasonable option.

In the grow-out feeds, there is no possibility for inclusion in the formulation as it is much more expensive than the alternative ingredients. The shadow price of freshwater shrimp meal is around 1000 USD/t.

Table 18. Adding freshwater shrimp meal at price of 1780 USD/t to tilapia starter feed formulation. The nutritional composition of all feeds was kept constant regardless of ingredient composition.

Nutrient	Starter feed (%, as is basis)
Freshwater shrimp	10
Fish meal (%)	-
Soybean meal (%)	15.2
Corn (%)	15.0
Wheat bran (%)	7.2
Feather meal (%)	10.0
Meat and bone meal (%)	12.7
Poultry meal (%)	10.5
Poultry blood meal (%)	10.0
Sunflower meal (%)	8.6
Methionine (%)	0.2
Lysine (%)	-
Vitamins and minerals premix (%)	0.4
DCP (%)	-
Price (USD/t)	857

The data presented here shows that freshwater shrimp meal is readily available for the animal feed industry in EA countries. It can be utilised in tilapia starter feeds at inclusion levels of up to 15%. Given the potential high cost of the product, it can also be employed as a feed additive to enhance palatability. However, the simplicity of current production methods may impact product quality, highlighting the need for the establishment of a professional industrial process to fully exploit this valuable resource.

3.1.6. Concluding remarks on alternative ingredients

The “alternative” ingredients tested in this study do not act as a “game changer” in feed formulation, as their commercial contribution is limited. These ingredients tend to exert more influence on the grow-out feed, given its lower demands in terms of protein and fat.

The pricing scenarios evaluated in our models assumed zero import taxes. The imposition of import taxes could significantly reduce the likelihood of incorporating imported ingredients into aquafeeds.

Among the tested ingredients, DDGS stands out as the most significant, with a relatively high inclusion level in the grow-out feed and a moderate impact on price (depending on tax-status). Sorghum might also be a viable alternative, especially when considering its price in comparison to corn.

Freshwater shrimp is currently too expensive to be included in grow-out tilapia feeds and it can only be used in starter feeds as an alternative to imported fish meal or as a palatability enhancer to improve grow-out feed quality.

Peanut meal, with no distinct advantages beyond being locally produced, holds marginal relevance. Given its current price closely aligning with the shadow price, its suitability for the industry may vary with price fluctuations, making it occasionally relevant. Further investigation and monitoring are warranted to assess its viability over time.

It is crucial to recognise that the effect on grow-out feed holds substantial importance for feed mill operations, considering that a significant portion (approximately 80%) of the tonnage produced consists of grow-out feeds. Moreover, the model presented here offers a snapshot of the current ingredient prices, but as prices have demonstrated high volatility in recent years, the economic contribution of each ingredient can change rapidly. Feed mills must maintain a diverse range of ingredients to effectively navigate and mitigate fluctuations in prices and availability.

3.2. Novel ingredients

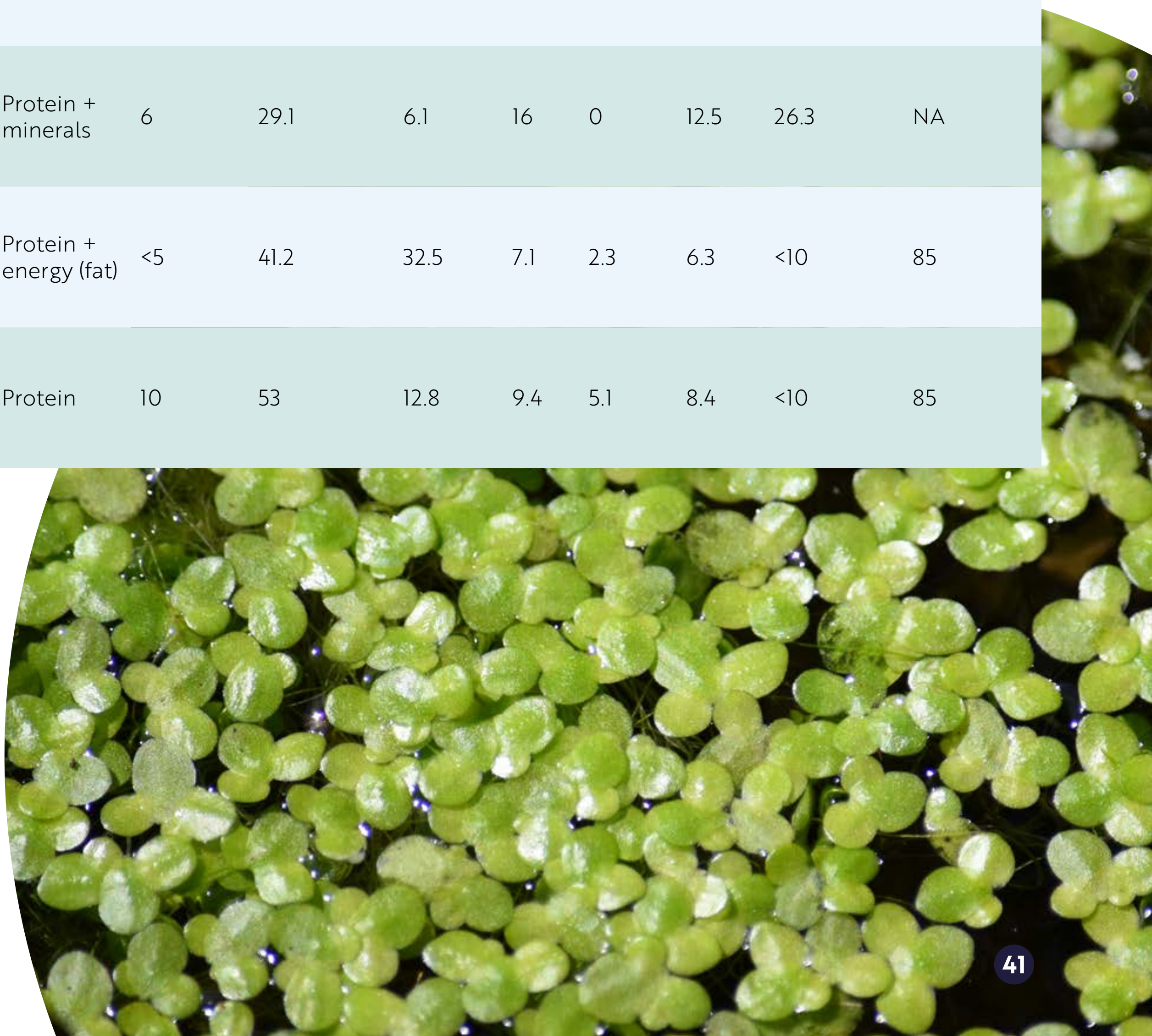
Globally, numerous potential ingredients are undergoing testing for their viability in the aquafeed sector. In this study, we focus on raw materials that can be locally sourced and produced. This emphasis aims to stimulate the local industry and expand the range of locally available ingredients. The novel ingredients under consideration are raw materials with the potential to become commercial ingredients for aquafeeds. These materials are currently not in widespread use, either in EA or elsewhere in the world.

The objective of this section is to assess the potential for developing novel ingredients and to estimate their viability as commercial ingredients for tilapia feeds in EA. This evaluation encompasses their nutritional value, technological readiness, and the estimated price necessary for them to compete with the conventional ingredients currently used in tilapia feeds in EA.

The readiness of technology for producing and commercialising these potential ingredients is a crucial factor. Utilising least-cost modelling, we have estimated the potential maximum price for each ingredient. Table 19 presents a list of the four most relevant ingredients and their nutritional content.

Table 19. Typical nutritional content of novel ingredients.

Ingredient	Ingredient purpose	Moisture (%)	Crude protein (%)	Crude fat (%)	Ash (%)	Chitin (%)	Fibre (%)	Carbohydrate (%)	Digestibility (%)
Yeast meal (brewers by-product)	Protein	8	42.6	1.0	6.6	0	3.2	39.6	70-77
Duckweed (Lemna minor)	Protein + minerals	6	29.1	6.1	16	0	12.5	26.3	NA
Dry BSF larvae (Hermetia illucens)	Protein + energy (fat)	<5	41.2	32.5	7.1	2.3	6.3	<10	85
BSF meal (Hermetia illucens)	Protein	10	53	12.8	9.4	5.1	8.4	<10	85



3.2.1. Yeast meal (brewery waste)

Microbial biomass (MB) is one of the future protein sources as its production is far more efficient and sustainable (in terms of resource use) than production of traditional protein sources. Within this newly developed industry, yeast is one of the most promising sources with a long history of diverse uses (e.g. breweries, bakeries and more).

Yeasts are single cell, eukaryotic microorganisms classified in the fungi kingdom. These microscopic fungi are generally about 3–4 µm in size, have a nuclear membrane and cell walls. There are about 60 different genera of yeast, which comprise about 1500 known species. Yeast are found in abundant quantities in almost every environment. Animals have been fed various forms of yeast and yeast derivatives for more than 100 years.

The intracellular chemical components of yeast cells vary among yeast species; nevertheless, all cell types include essential amino acids, peptides, carbohydrates, salts, monosodium glutamate, nucleic acids (RNA), enzymes, and cofactors. Yeast cell walls are composed of glucans, glycoproteins, mannans, and chitin. The combination of these compounds makes them attractive not only as nutritional supplements in animal feeds, but also useful nutraceuticals.

Multiple yeast products are available in the market, with the most widely used ones being by-products from breweries. Another category includes yeast biomass specifically cultivated for animal feed. This study focuses solely on yeast by-products since the fermentation of single-cell yeast as a feed source is still technologically immature.

3.2.1.1. Nutrition and quality considerations

The nutritional composition of brewer's yeast meal (BYM) is contingent upon the product type and yeast species. Typically, yeast products derived from brewery by-products contain approximately 35-40% protein (Table 29). With protein content ranging from 37% to 44%, BYM can be a viable protein source for tilapia feeds. Tilapia demonstrate a protein digestibility for BYM ranging from 70% (Zerai et al., 2008) to 77.1% (Gokulakrishnan et al., 2023). The amino acid composition of Brewer's Yeast varies based on fermentation protocols and the type of grain used. The essential amino acid profile reveals elevated levels of lysine and reasonable levels of methionine, making BYM well-suited as a protein source for tilapia feeds. Notably, the presence of high quantities of glutamate, a known feed attractant, in BYM suggests a potential positive impact on feed palatability.

Brewer's yeast meal is characterised by low lipid content, high ash content, and moderate levels of carbohydrates. The fatty acid composition is predominantly composed of unsaturated fatty acids, while the carbohydrates consist mainly of polysaccharides and starch at a level of about 10% that remain from the fermentation process.

Like any other microbial protein, BYM contains significant amounts of non-protein nitrogen (NPN) in the form of nucleic acids, which can lower crude protein levels at about 15%. While the elevated levels of nucleic acids in yeast meals might limit their use in feeds for most monogastric animals, fish can tolerate and metabolise high levels of uric acid. This allows for increased inclusion levels of dietary yeast, potentially up to 25% of the formulation. Brewer's yeast meal has high nutritional value as a protein source, but in addition to that, BYM contains a wide range of bioactive molecules that have been shown to affect the health of the farmed fish. These might include the following benefits:

- Prebiotics: The cell wall represents about 15–20% of the dry weight of yeast cells, and the main polysaccharide fractions are β-glucans and mannans that have been shown to have immuno-stimulation and prebiotic properties.
- Toxin binder: Yeast and yeast cell wall derivatives appear to have some ability to bind mycotoxins (aflatoxins, ochratoxin A, T-2 toxin, and zearalenone) and minimise their adverse effects on animal health and performance.
- Nucleotides: BYM is also a concentrated source of nucleotides that have been shown to improve intestinal morphology and function, immune response, composition of intestinal microbiota, liver function and morphology, as well as growth performance.
- Palatability enhancer: Yeast is considered to enhance feed palatability, which is often related to high glutamate content in combination with high levels of nucleic acids.
- Natural source of vitamins and minerals: Yeast is a rich source of natural vitamins, especially from the B complex. Yeast contains relatively low levels of ash, but has high phosphorous content and good digestibility in all fish.

3.2.1.2. Supply

Brewer's yeast has been used in aquafeeds since the 1990s and is available globally due to its prevalence as a by-product of beer breweries, with a production rate of 2.3 kg per m3 of the final product (Gokulakrishnan et al., 2023). Using a yeast production ratio of 2.3 kg/m3, it can be estimated that brewer's yeast production was about 423,000 tonnes in 2011 (FAO, 2016). The estimated beer production in EA in 2022 was 3.8 million m3 and by applying the same ratio of 2.3kg/m3, it is estimated that the potential of BYM in EA is 8,740 tonnes per year. Beer is produced in EA all year round and therefore the raw material is expected to be available accordingly.

3.2.1.3. Cost and production

The Free On Board price (global supply) of brewer's yeast meal is estimated at 600 USD/t, equating to 768 USD/t at the feed mill gate in EA; higher than most plant ingredients like soybean meal but comparable to prices of animal by-products. While brewer's yeast by-products are widely available globally, not all regions have downstream facilities to convert wet by-products into dry meals. In instances where proper facilities are lacking, brewer's yeast by-products might be disposed into the environment.

3.2.1.4. Reference for use in tilapia feeds

The expected digestion level of yeast products by tilapia stems from their potential capability to break down the yeast cell wall and their capacity to adapt to diets enriched with nucleotides. Research studies (Zerai et al., 2008, Gokulakrishnan et al., 2023) on the use of brewer's yeast meal in tilapia feeds indicate that inclusion levels of up to 15% enhance the growth rate and health of cultured tilapia. However, at inclusion levels exceeding 25%, a decline in fish performance occurs, likely due to a reduction in feeding rate (Zerai et al., 2008).

In many markets, the cost of brewer's yeast meal is too high to be cost effective as a protein source in tilapia feeds. Therefore, many nutritional studies focus on evaluating BYM as a feed additive that is included at concentrations of about 1-2%.

3.2.1.5. Least cost formulation

The potential contribution of brewer's yeast meal was tested by applying the least cost method into a typical tilapia feed. The models indicate that at a price of 768 USD/t, brewer's yeast emerges as a pertinent ingredient for tilapia feed production, as illustrated in Table 20. The optimum economic contribution is observed in starter feeds, where it can effectively substitute 50% of the fish meal, a crucial component in this formulation. This substitution allows for a reduction of 36 USD/t in the formula price, constituting over 4% of the total formula cost.

Brewer's yeast is also incorporated into the early grow-out feed at a moderate level of 4.5% and into the grow-out feed at a substantial level of 8.5%; in both formulas the economical contribution is moderate, at a level of 2-3% of total formula price. Consequently, it is established that this ingredient represents a viable and advantageous alternative for the tilapia feed industry.

Table 20. Adding brewer's yeast at price of 768 USD/t to 3 tilapia feed formulation. The nutritional composition of all feeds was kept constant regardless of ingredient composition.

Nutrient	Starter feed (%, as is basis)	Early grow-out feed (2mm)	Grow-out feed (4.5mm)
Brewer's yeast	5.0	4.5	8.5
Fish meal (%)	5.0	-	-
Soybean meal (%)	12.6	5.0	19.7
Corn (%)	15.0	30.4	28.9
Wheat bran (%)	7.9	10.0	15.0
Feather meal (%)	10.0	-	-
Meat and bone meal (%)	12.9	15.0	15.0
Poultry meal (%)	12.6	11.5	-
Poultry blood meal (%)	10.0	7.5	2.0
Sunflower meal (%)	8.2	12.0	10.0
Methionine (%)	0.2	0.2	0.2
Lysine (%)	0.2	0.2	0.4
Vitamins and minerals premix (%)	0.4	0.3	0.3
DCP (%)	0	0	0
Price (USD/t)	818	616	522

In conclusion, brewer's yeast meal stands out as a globally available and consistently abundant ingredient. Its utilisation in EA is recommended, given its high protein quality (with high digestibility and a balanced amino acid profile) and affordable price. The economic advantages of using brewer's yeast meal are particularly pronounced in regions where processing plants are operational, although aggregation and drying to a usable meal may provide hurdles.

3.2.2. Black soldier fly (BSF)

Insects have garnered significant attention as a novel protein source for aquafeeds, with substantial investments totalling hundreds of millions of dollars dedicated to the development of this industry in recent years. While insects have been utilised for many years, only in the past 3-4 decades have serious efforts been initiated to industrially produce insect meal as a macro ingredient, particularly as an aquafeed protein source. The production of insect meal is experiencing rapid growth globally, with significant developments observed in regions such as China, Southeast Asia, Europe, North America, and Australia.

To date, a minimum of eight insect species have undergone testing and implementation for industrial aquafeed production, including: silkworms (Bombyx mori), black soldier fly (Hermetia illucens), housefly (Musca domestica), yellow mealworm (Tenebrio molitor), lesser mealworm (Alphitobius diaperinus), house cricket (Acheta domesticus), banded cricket (Gryllodes sigillatus) and Jamaican field cricket (Gryllus assimilis) (Alfiko et al., 2022).

Approval for their use in the production of aquafeed was granted to most of these insect species by EU legislation in 2017 (European Commission, 2017). This review focuses exclusively on the black soldier fly (BSF) as an ingredient for tilapia feeds, given its significance and heightened attention within the aquafeed industry and presence in EA.

3.2.2.1 Nutrition and quality considerations

BSF has been highlighted as one of the most promising insect meals because it has a high content of protein and fat. Due to the high content of fat in the BSF larvae, most commercial products are sold as BSF meals that are defatted, dried and ground. The dry body composition of BSF larvae comprises 40-50% of crude protein, followed by 30-35% lipids and about 10% of ash. The defatted meal contains >50% protein and around 15% fat (Table 19). The biochemical composition of BSF larvae can change significantly depending on conditions such as the time of harvest. The maximum percentage of crude protein content is found in five-day-old larvae, with a gradual decrease in protein content observed at increasing age (Mohan et al., 2022).

Protein quality of BSF meal is relatively good, it is comparable to other animal proteins and superior to plant proteins. Protein digestibility is >85% (Protix, 2023) although chitin might reduce digestibility in several fish species, including tilapia. The essential amino acid profile is balanced and meets the amino acid requirements of tilapia, having levels of lysine and methionine that are comparable to the amounts found in fish meal.

BSF larvae have relatively high fat content, comprising 58%-72% saturated fatty acids and 19%-40% mono and polyunsaturated fatty acids (Mohan et al., 2022).. The fatty acid composition of BSF larvae may pose challenges for their incorporation into fish feed, primarily due to their low levels of essential fatty acids and the presence of up to 61% lauric acid and, to a lesser extent, myristic acid. However, these medium-chain triglycerides (MCT) have gained attention in livestock and human nutrition for their rapid absorption, oxidation, antimicrobial and antiviral properties.

3.2.2.2. Supply

The amount of BSF meals available in global markets is limited, with an estimated annual production of about 4,000 tonnes per year (at EU standards). This quantity is utilised for the production of approximately 10,000 tonnes of feed (IPIFF, 2023). Projections suggest that only around 17,000 tonnes of insect meal will be produced in 2030 (NCE, 2023). The product is available all year round and can be purchased globally.

3.2.2.3. Cost and production

Insects offer the distinct advantage of thriving on organic side-streams, making a significant contribution to a circular economy. BSF, for instance, exhibits the ability to bio-convert a diverse range of organic waste into nutrient-rich animal feeds and plant fertilizer. The efficiency of insect cultivation stems from their capacity to be grown in high densities, making it a land-efficient industry. Additionally, insect production requires minimal freshwater, generates minimal waste, and has low CO^2 emissions.

Despite these eco-friendly attributes, production costs are notably high, especially in large-scale industrial production when consistent substrates are required. The current global market price of defatted BSF meal is 3500-4000 USD/t (Free On Board price) and with added transportations costs to EA, the price in the feed mills would easily be >4000 USD/t.

Throughout this research, we did not come across any commercial production of insect meals in EA that yields a sufficient amount to be relevant to the aquafeed industry in the region. However, there is increasing activity in commercial production of insect meals in East Africa by key players such as Sanergy, InsectiPro and a range of other producers targeting significant scale. Production systems are still nascent and while early signs show that local prices of defatted, dried and ground BSF can be competitive against global prices (potentially up to half prevailing market prices), the product would remain cost-prohibitive against cheaper existing raw materials such as soya meal and even fish meal.

3.2.2.4. Reference for use in tilapia feeds

Numerous studies have explored the utilisation of BSF meals in fish feed, including tilapia feeds. Overall, these studies consistently demonstrate that BSF meal can be incorporated into fish feeds, including tilapia diets, at high inclusion levels of up to 30%, without any discernible adverse effects on growth or other quantitative parameters across various fish species (Mohan et al,. 2022). In a specific study involving tilapia fry (Oreochromis niloticus), where varying amounts of BSF meal were gradually introduced up to a level of 42%, the results indicated that growth rates remained unaffected and the health of the liver and intestine showed no adverse effects at BSF inclusion levels of up to 31.7% (Limbu et al., 2022).

The high fat level in BSF larvae and the fat composition might affect the use of BSF, as studies in rodents and humans indicate that Medium Chain Triglyceride (MCT) consumption is linked to decreased feed intake and reduced fat deposition (Belghit et al., 2019). In the case of fish, dietary MCT has been associated with increased absorption of protein, lipid, and starch. However, a negative correlation exists between MCT intake and growth, feed intake, and fat deposition in fish (Belghit et al., 2019). Therefore, the fatty acid profile of BSF becomes a limiting factor in its application in aquafeed, both due to the deficiency in essential fatty acids and the potential excess of MCT. However, whole BSF larvae have been used in Uganda as a supplementary feed in pond raised tilapia, where they were actively consumed by the fish and provided comparable growth to feeding conventional pellets (KTN, 2022).

Black Soldier Fly (BSF) meal is commonly promoted as a potential substitute for fish meal, and it can indeed replace some of the fish meal in certain applications. However, it cannot serve as a complete substitution for most fish species because BSF meal lacks some essential amino acids, minerals and micronutrients present in fish meal – which also acts as a feed palatability enhancer.

3.2.2.5. Least cost formulation

The current price of defatted, dried and ground BSF is significantly higher than that of all other ingredients. At its current price range of 3500-4000 USD/t, it is not economically feasible to include it in any of the three tilapia feeds. For instance, the cost of BSF is over two times more expensive than fish meal, despite having lower protein levels and inferiority in nutrient composition and palatability. Given the nutritional value of BSF, models suggest that the price of this ingredient included in tilapia feeds should be reduced to around 1100 USD/t.

The main obstacle to adopting BSF meal, along with other insect meals, is their considerable cost, making them less economically viable. Nonetheless, many consider BSF meal to be a highly promising novel ingredient. Its nutritional profile features elevated protein levels with excellent digestibility and a well-balanced amino acid composition. Additionally, the product exhibits low levels of ANFs, although it does contain moderate levels of chitin and an unbalanced fatty acid profile, presenting some challenges. Feeding experiments have shown that BSF meal can be successfully incorporated into fish feeds at inclusion levels of up to 30%.

It is important to note that the high production cost in global markets is influenced by stringent EU regulations, which restrict the types of feed substrates that can be used. This implies that production in East Africa, if scaled, could be cheaper since no stringent regulations are currently imposed on BSF production. However, the challenge of inefficient consolidation and collection of substrate into the production centres is yet to be resolved, and is further compounded by the need for consistency in substrate nutritional profile in order to deliver a consistent nutritional profile in the BSF meal.

3.2.3 Duckweed

Duckweed belongs to the family Lemnaceae that constitutes several species (i.e., Spirodella polyrrhiza, Wolffia arrhiza, Lemna minor and L. gibba) that can be used as a protein and micronutrient source for macrophagous fish (Azim and Wahab 2003; Mandal et al. 2010) and herbivorous fish (Singh et al. 1967; Gaigher et al. 1984).

3.2.3.1 Nutrition and quality considerations

Duckweeds are a protein source (Table 21) that are rich in essential amino acids compared to most other conventional plant proteins (Kabir et al. 2009), and closely resemble the protein of animal origin (Hillman and Culley 1978; Journey et al. 1991; Bairagi et al. 2002; Yilmaz et al. 2004; Aslam et al. 2016; Asimi et al. 2018).

Table 20. Adding brewer's yeast at price of 768 USD/t to 3 tilapia feed formulation. The nutritional composition of all feeds was kept constant regardless of ingredient composition.

Duckweed species	Dry matter	Crude protein	Fat	Crude fibre	Ash
L. gibba	4.6	25.2	4.7	9.4	14.1
S. punctata	5.2	28.7	5.5	9.2	23.7
S. polyrhiza	5.1	29.1	4.5	8.8	15.2
W. columbiana	8.8	36.5	6.6	11.0	17.1

Source: Rusoff et al. (1980)

Duckweed protein is characterised by high availability and absorption of amino acids, including lysine and methionine (Cruz et al. 2011; Cruz et al. 2015), as well as of vitamins A, B and E and carotenoids (Chojnacka, 2006; Showqi et al. 2017). Duckweeds possess 39% essential, 54% nonessential and 7% non-proteinogenic amino acids (Chakrabarti et al. 2018). They are rich in threonine, leucine, phenylalanine, valine and isoleucine (Goopy and Murray 2003), serine, glycine, methionine, tyrosine, histidine, lysine (Table 22; Yilmaz et al. 2004).

Table 22. Amino acid composition of four duckweed species (g/100 g).

Amino acid	**Duckweed species**			
	L. gibba	**S. punctata**	**S. polyrhiza**	**W. columbiana**
Alanine	4.59	4.48	4.79	3.75
Arginine	4.29	5.25	4.86	3.78
Aspartic	7.12	7.55	7.38	5.63
Glutamic	7.60	8.00	7.69	5.76
Glycine	3.79	3.95	3.93	3.04
Histadine	1.89	2.15	1.90	1.18
Isoleucine	3.87	3.75	3.76	3.06
Leucine	7.15	6.85	6.88	5.83
Lysine	4.13	4.30	4.26	3.37
Methionine	0.83	0.83	1.07	0.87
Phenylalanine	4.45	4.20	4.38	3.60
Proline	2.93	3.28	2.95	2.41
Serine	2.61	2.80	2.83	2.28
Threonine	3.20	3.45	3.31	2.55
Tyrosine	2.91	3.05	3.14	2.17
Valine	4.96	4.40	4.71	3.49

Source: Rusoff et al. (1980)

Duckweed contains several carbohydrates such as starch cellulose, trace hemicellulose, pectin, etc. The specific carbohydrate content of duckweed is influenced by species, climate and culture medium. The starch content is in the range of 4-10% per dry weight, while the polyunsaturated fatty acids account for 48-71% of the lipid fraction (Diwan and Kaur, 2023).

The mineral content of the duckweed could be easily manipulated by adjusting the composition of the nutrient medium. Duckweed contains high levels of minerals such as Ca, P, Na, K, Mg, Fe, Mn, Cu, and Zn compared to the routinely utilised cereals and grains, such as chickpea, corn and soybean (Diwan and Kaur, 2023).

3.2.3.2. Supply

Duckweed typically consists of only 6-8% dry matter, meaning that much of the fresh biomass is lost during the drying process. The high-water content of the duckweeds makes them extremely bulky and perishable when harvested (Heuzé and Tran, 2015) and artificial drying is costly. A trial in the Netherlands required 30 hours at 40°C to decrease moisture from 95 to 10% (Holshof et al., 2009). Natural, and potentially less expensive methods such as sun-drying, drying in the shade, or air-drying, are therefore preferable, but would equally require vast space, which may not be available. Generally, duckweed in not farmed commercially in EA, although it is naturally abundant in various regions of Africa, including EA, due to its ability to grow rapidly in aquatic environments. Given the relatively straightforward production technology, the main hurdle remains the economic viability of industrialisation.

3.2.3.3. Cost and production

Presently, the market demand for duckweed is almost non-existent in EA, meaning that its pricing is difficult to determine. The cost of producing duckweed is dependent on several factors, including cultivation methods, operational expenses, and market dynamics. Different cultivation methods (such as open ponds, closed bioreactors, or wastewater treatment systems) have varying costs associated with infrastructure, land use, and labour (Bergmann et al., 2000; Appenroth et al., 2017). Duckweed cultivation utilises inputs such as nutrients, water, and energy whose costs must be evaluated prior to establishing the business enterprise. Moreover, the type and quantity of inputs per tonne of duckweed produced significantly affect the price of the final product (Sarker et al., 2019; Vagner et al., 2021).

3.2.3.4. Reference for use in tilapia feeds

Feeding trials have demonstrated that tilapia and carp efficiently convert duckweed to biomass (Hassan & Edwards, 1992; Asimi et al., 2018). Duckweed (Lemna minor) can be incorporated into the diet at levels ranging from 15% to 25%, with 15% being the recommended by Yen et al., 2015. Duckweed offers several nutritional advantages. Its high lysine concentration, elevated mineral content and natural carotenoids that contribute to improved fish growth and feed utilisation, even at low temperatures (Yilmaz et al., 2004).

3.2.3.5. Least cost formulation - Duckweed

As there is currently no estimated cost for duckweed due to its lack of commercial production, its inclusion into standard tilapia feed was modelled based on its nutritional content. The model indicates a shadow price for duckweed of approximately 700 USD/t. This price stands out significantly compared to other plant materials such as DDGS, which has a shadow price of about 500-550 USD/t. This exceptional value is likely attributed to the remarkably high levels of essential amino acids, particularly lysine and methionine, found in duckweed.

3.2.4. Concluding remarks on novel ingredients

In summary, this study highlights a significant hurdle in the adoption and integration of novel ingredients, primarily centred around their production technologies and their pricing relative to conventional ingredients. Among the ingredients considered, only brewer's yeast, modelled at a relatively low price, demonstrates promising potential as a viable component for tilapia feeds.

While black soldier fly larvae (BSF) meal holds substantial promise as a locally produced ingredient contributing to waste treatment, its current price is prohibitively high and far from being competitive in tilapia feeds. Production costs will need to substantially decrease if BSF is to realise market penetration; to approximately one-third of its current market price to position it as a feasible alternative for tilapia feeds.

Duckweed has nutritional potential to become an ingredient for aquafeeds and it seems that its potential price could be higher compared to other plant materials. However, it seems that the level of technological readiness is low, beyond the level that even a market price could be evaluated.

4. Sustainability considerations

It is crucial to find the right basket of feed ingredients that are available, affordable, have a low environmental footprint, avoid food and feed competition, and most importantly, meet the nutritional requirements of the farmed fish. In this section, the main considerations are discussed to balance the socio-economic and environmental performance of feed as best as possible.

1

It is preferential to source locally produced ingredients and use land, water and nutrients efficiently, while avoiding pressure on ecosystems and biodiversity (FAO, 2011; Foley, 2011). In this regard, ingredients with minimum pressure on freshwater, marine and agriculture systems, such as side streams/by-products, should be prioritised (Malcorps et al., 2023).

2

Feed provisioning is a crucial component in the sustainable intensification process of any livestock farming (Little et al., 2018), because it constitutes the highest proportion of the production cost, determines enterprise profitability, and impacts the environment within which marine and freshwater aquaculture is executed (Bohnes et al., 2018; Rana, Siriwardena and Hasan, 2009; Henriksson et al., 2018; Marín et al., 2019).

3

Tilapia feed formulations in EA rely on a variety of ingredients (Table 1), but the inclusion of fishmeal is minimal because of the high cost. While there are environmental concerns regarding the use of fishmeal and fish oil, this is equally the case for plant derived meals and concentrates (Newton and Little, 2018; Blanchard et al., 2017; Malcorps et al., 2019). Producing these crops increases demand for agricultural resources, such as land, water and fertiliser that can lead to biodiversity loss, greenhouse gas emissions, eutrophication and food and feed competition (Appendix 7).

4

Despite the high cost of fish meal, a strategic inclusion is recommended to stimulate consumption, digestibility and fish welfare, while it also affects the micro- and macronutrient levels in the final fish product (Glencross, 2020; Newton et al., 2023; Sprague, Dick and Tocher, 2016; Nichols et al., 2014; Saito et al., 2020).

5. Readiness

In EA, over 70% of the fish feeds are imported, and only 30% is made locally (in factories and on-farm). Imported feeds are expensive, but local feeds are generally perceived to be of lower quality. To grow a credible local feed industry to meet the growth ambitions for the sector, key hurdles need to be overcome. Primary amongst these is price: a distinctive feature of the ingredient market in EA is generally higher cost compared to other global locations, particularly for imported raw materials, due to relatively lower volume demand, increased transportation costs and considerable distances involved in shipping. Quality must be addressed to ensure farming efficiency and bolster reputation: this is a challenge in all feed sectors, but particularly challenging in an emerging sector that demands relatively small volumes on a global scale. Ingredient availability needs to be improved by ensuring as wide a basket of options as possible, alongside scaling local production. Availability includes an assessment of the technological maturity of ingredient production, as considered in Table 23. These challenges have pointed to the identification of local ingredient options that could help unlock the potential of the aquaculture industry in East Africa.

By promoting innovation, technology transfer, and capacity building in aquafeed production, EA countries can strengthen their aquaculture sectors, while contributing to food security, economic growth, and environmental sustainability in the region. Investors need to collaborate with researchers, policymakers, and industry stakeholders to enhance the availability, affordability, and sustainability of fish feed ingredients and feeds in EA. Adherence to quality and safety standards set by national regulatory agencies needs to be improved as it is essential in ensuring the nutritional adequacy and safety of fish feeds.

Table 23: Ingredient readiness level of selected alternative and novel ingredients within EA and globally.

Ingredient	EA TRL	Global TRL	Reason
Canola meal	2	9	Canola is an ingredient widely used in the fish feed industry. However, it is not grown in sufficient quantities within EA, and would therefore need to be imported from Europe or North America. The logistics and cost associated with the importation of Canola is currently quite prohibitive. Scaling local production would take time.
DDGS	2	9	This ingredient is widely used within the global fish feed industry, but corn based DDGS is not available within Africa and would need to be imported from Europe or North America.
Freshwater shrimp	7	1	FWS meal is being used in small and large feed mills in EA (Key Informant, Industry). It is being tested for inclusion at a rate of 15%.
Peanut meal	6	9	Peanut meal has been used in small to large feed mills in EA (Key Informant, Industry). Its challenges are the ANFs limiting its widespread usage and the procurement of peanut meal in sufficient quantities. Further trialling may be necessary to bolster widespread adoption.
Sorghum	4	9	Sorghum has been used in small to large feed mills in EA (Key Informant, Industry). Its challenges are the ANFs in a number of Sorghum varieties, limiting its widespread usage and the price point. Further trialling may be necessary to bolster widespread adoption.
BSF	4	6	BSF meal has been used in pilot testing in some feed mills around the world. It has been trialled in EA (Key Informant, Industry). Its challenges are the volumes available on the market limiting its widespread usage and the high price point.
Duckweed	4	4	Duckweed has been used in pilot trials but not at commercial scale. Its main TRL challenges occur because there are no commercial volumes available on the market and the large volume required to produce the dried quantities needed.
Yeast/ Brewery waste	4	4	This ingredient is widely used within the fish feed industry, but processed brewery waste is not available within East Africa and a new industry would need to be established to dry and process it for the commercial market.

6. Recommendations

This evaluation has focused on underutilised ingredients, especially by-products from plant and animal processing, and emerging ingredients to improve the competitiveness, efficiency and sustainability of the aquaculture feed sector in EA.

Four novel and alternative ingredients have been identified with the highest potential for production for inclusion in aquafeeds in EA. It is important to note that currently, none of these ingredients are readily available for inclusion in aquafeeds, and each requires proactive measures to transform them into viable ingredients.

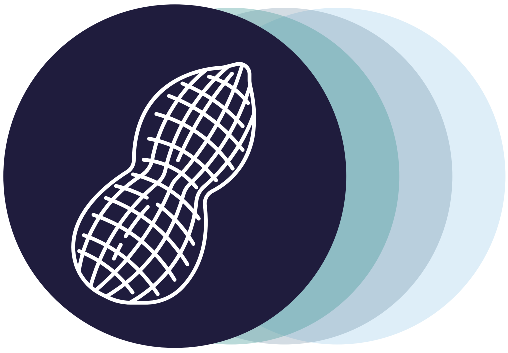
Additionally, a conventional ingredient with promising potential for scaling local production is highlighted: Processed Animal Proteins (PAPs) from rendering animal processing by-products, particularly poultry. While these products are already in the market, their high prices result from importation. Local production has the potential to make these crucial ingredients more affordable, contributing significantly to the overall sustainability and economic viability of the aquafeed industry in EA.

Brewer's yeast

As demonstrated in the modelling section, brewer's yeast exhibits significant potential for inclusion in aquafeeds due to its cost-effectiveness and numerous benefits that enhance feed quality, subsequently improving fish performance. In the EA region, annual beer production in 2022 was reported to be 3.8 million m3 resulting in an estimated quantity of dried brewery by-products of 8740 tons per year (calculated at a rate of 2.3 kg/m3). With a potential inclusion level of 10%, this amount of yeast could be integrated into nearly 90,000 tonnes of feed annually.

The primary challenge in harnessing this potential lies in the absence of a production system capable of collecting brewery waste, drying it, and subsequently packaging it. The production lines for drying wet brewery spent grains typically involve standard machinery in a two-step process: The first step is a screw dehydrator that reduces the initial moisture content (usually over 80%) to about 60%. The second step involves a disc dryer that further reduces the moisture content to approximately 10%. After drying, there is a cooling step, and sometimes grinding and bagging follow.

Assuming a selling price of at least 800 USD/t, this operation could generate an annual income of approximately 7 million USD. The economic viability and potential profitability appears to justify investments in establishing a production facility for brewer's yeast meal.



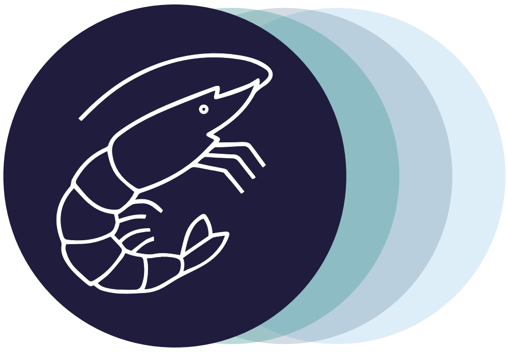
Peanut meal

Peanut meal, despite being a major product of groundnut production in Africa, is presently underutilised in EA. The reluctance to incorporate this ingredient into feeds in the region stems from two main factors: the prevalent contamination with mycotoxins and the perception among feed millers that its nutritional quality is inferior to other oilseed cakes.

The documented high frequency of toxic levels of mycotoxins presents a genuine obstacle, limiting the safe use of peanut meal in fish feeds. However, our literature review suggests that technical methods exist to exclude toxins from the meal: aqueous ammonia has been effective in detoxification of aflatoxin but requires strict safety regulations. Other detoxification processes, like using hydrogen peroxide, formaldehyde, and calcium hydroxide, are effective but complicate the use of PM and increase product prices.

This implies that the product can be pre-treated, making it safe for distribution. Alternatively, implementing preventive measures, especially in the production chain of peanut meal for larger producers, can result in benchmarked products that are safe for use.

Despite the potential, there is a noticeable lack of sufficient scientific studies on the use of peanut meal in tilapia feeds. This gap contributes to the reluctance of professional feed millers in the region to accept this ingredient. To the best of our understanding, the nutritional potential of peanut meal in tilapia feed is promising. Combined with its local availability and reasonable cost-effectiveness, it holds significant potential to become a substantial ingredient in aquafeeds as long as quality can be assured. Further research and awareness could help bridge the gap in understanding and promote the acceptance of peanut meal in tilapia feeds among feed millers.



Freshwater shrimp

Freshwater shrimp represents a valuable resource that is currently underutilised in EA, despite constituting a significant portion of the biomass in Lake Victoria. The yield of this resource is relatively low, accompanied by generally low product quality and relatively high prices.

The utilisation of freshwater shrimp in aquafeeds requires careful management, considering the need for controlled fishing to prevent the collapse of the shrimp population. Additionally, a portion of the shrimp catch is directly consumed by humans. Despite these challenges, the potential amount of shrimp in the lake is enormous, and the fishing potential is yet to be fully exploited. One of the key obstacles is the lack of professional fishing practices, with the current landed shrimp being a result of bycatch rather than intentional fishing.

Furthermore, the absence of production facilities for high-quality shrimp meal contributes to the underutilisation of this resource. Key Informants have reported that direct working relationships with processors have enabled the quality of this product to be improved. The required machinery is similar to that used in producing other animal proteins, as detailed in the PAP production section.

While shrimp meal is an expensive ingredient and not essential as a macro ingredient in most tilapia feeds, it plays a crucial role in starter feeds, potentially replacing imported fish meal. Additionally, small quantities (less than 5%) of shrimp meal can be added to grow-out feeds to enhance feed quality in terms of palatability and provide a natural supply of micronutrients.

Sorghum

Sorghum stands out in this context as a carbohydrate source with relatively low value and impact on feed prices. It serves as an alternative to corn (maize) and primarily contributes technically to aquafeed by acting as a pellet binder in the extrusion process.

Currently, the price of sorghum is comparable to that of maize, albeit slightly more expensive (335 and 370 USD/t, respectively as of November 2023). This pricing dynamic is subject to change based on market availability. Sorghum holds the potential to become a significant ingredient in aquafeeds, particularly as it is produced in regions with semi-arid climates where alternative crops may be limited. However, its underutilisation in aquafeeds is not solely due to cost efficiency but also stems from the fact that certain sorghum varieties are unsuitable for fish feeding due to the presence of ANFs.

To fully leverage the potential of sorghum in aquafeeds, it is crucial to identify sorghum varieties with low levels of ANFs while remaining cost-effective and competitive compared to maize. This involves careful consideration of both nutritional suitability and economic factors to ensure the optimal inclusion of sorghum in aquafeed formulations. Publishing the information on the right sorghum varieties can help the industry to be selective and increase the utilisation of this ingredient in aquafeed.

Processed Animal Proteins (PAPs)

PAP (Processed Animal Protein) meals play a crucial role in fish feeds in EA, including formulations for various fish types, notably tilapia. PAPS, such as meat and bone and feather meal, are cost-effective sources of crude protein, essential amino acids, and minerals; and often have higher contents than rapeseed and soy (EFPRA, 2023).

However, the cost of these products in EA is unusually high compared to other global markets, such as the European market. The primary contributor to this cost disparity is the elevated transportation costs, among other factors for imported sources. To address this challenge and enhance cost-effectiveness, local production of these products within the region should be scaled. The use of PAPs shows potential in EA because it produced 1.85 MMT of meat in 2021 destined for domestic consumption and exports, in which 1 MMT was represented by beef and buffalo, 0.28 MMT by sheep and goat, 0.26 by poultry and 0.20 by pig. On average, an estimated 30% of this supply would be considered by-products.

A significant proportion of the livestock industry is fragmented, which limits the collection and utilisation of animal by-products significantly (KI, academic). This distribution makes it challenging to collect the offal, which serves as the primary ingredient for PAP meals. An additional, significant obstacle is the lack of proper production equipment. The production process involves multiple steps, including cooking raw materials, fat extraction through squeezing, and subsequent drying and bagging. The complexity of the production process requires the separation of different raw materials, such as feathers, meat and bone, and blood, each needing separate processing.

Given the current market prices exceeding 1000 USD/t and the amount of animal by-products available across EA, investing in such technology appears viable and could contribute to addressing the challenges of feed ingredient sourcing in EA.

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Annexes

Annex 1: SWOT

Strengths	Opportunities
• The fast-growing population increases demand for livestock and fish products, which drives feed demand. • EA has vast natural resources, including land suitable for agriculture and livestock production, which can be utilised for feed production. • EA governments and international organisations are recognizing the importance of the agricultural sector, leading to increased investments in intensification. • Availability of local feed ingredients in EA, such as soy, sunflower, wheat, maize, sorghum, and agro-industry by-products, reduces dependency on imports.	• Production and processing of feed ingredients within EA Africa should be prioritised to enhance economies of scale, competitiveness, quality and specific nutritional needs, while reducing dependency on imports. • Regional (research) collaboration could add value to increase availability of feed ingredients in EA and export surplus. • Investing in innovation can lead to the development of new feed ingredients and improved feed formulations. • Upscaling and intensification of agriculture in EA increases crop and by-product output, therefore feed availability.
Weaknesses	**Threats**
• The inadequate transportation, storage facilities and traceability capacity in EA affects quality, control and availability of feed. • Lack of intensive agriculture leads to higher production costs and reduced competitiveness. • Inconsistent quality control measures can lead to variations in feed quality, impacting animal health and productivity. • Insufficient research on production and processing of different ingredients limits their use in innovative feed formulation and production processes. • Reliance on imports reduces resilience of the EA aquafeed sector.	• Food and feed competition, as well as internal competition between livestock and aquafeed. • Weather variability (floods and droughts) and climate change disrupt agriculture crop yields and therefore availability of raw materials and by-products for feed ingredients. • Diseases and pests which can damage crop production. • Global events, such as climate change, political instability, conflict or economic disruptions, can affect the prices of imported feed ingredients and additives. • Policies and regulations could negatively affect availability of feed ingredients.

Annex 2: Processed Animal Proteins

The rendering of animal by-products can significantly contribute to and promote the animal sector in EA. Here are some key points:

- Production of Valuable Animal Proteins: Rendering allows production of valuable animal proteins, which can be used in the animal feed industry. This reduces the reliance on imported meals and boosts the local agricultural economy.

- Improved Animal Feed Quality: The availability of locally produced animal by-product meals, including fish meals, would greatly enhance the quality of animal feed in EA. This, in turn, would lead to increased farm yields and improved livestock health.

- Extra Income: Rendering by-products that are currently wasted or improperly utilized can provide an additional source of income for the animal production sector value chain. This creates economic opportunities and increases the overall profitability of the industry.

- Sanitation and Disease Control: Professional treatment of animal by-products through rendering enhances sanitation practices within the livestock industry. This, in turn, reduces the risk of disease transmission and promotes overall animal health.

Potential by-products that can be rendered in EA include:

- Fish Meal: Given the proximity of EA countries to Lake Victoria, a significant source of fishery products, the utilisation of underutilised fish by-catch can greatly contribute to the aquafeed sector. Proper rendering ensures that this valuable resource is utilised efficiently.

- Poultry By-Products: Commercial slaughterhouses can provide poultry by-products such as meat and bones, feathers, and potentially blood. Proper rendering of these by-products ensures their value is maximized, even including the rendering of whole diseased animals and hatchery by-products in certain circumstances.

- Ruminant by products – depends on regulation of each country.

- Pig by products - depends on regulation and also includes discussion on public acceptance.

While substantial volumes of animal by-products are present in certain slaughterhouses in EA, the next stage is missing, which is the rendering plants to process by-products into e.g., meat and bonemeal (KI, academic). This indicates opportunities for investors to establish a rendering sector for processing animal by-products into feed ingredients. Various options for processing machinery are available. The “conventional” method, exemplified by producers like Haarslev is suitable for relatively large-scale production. However, its flexibility is limited as each raw material necessitates a distinct setup and configuration.

A second alternative, exemplified by companies like Celitron, offers more innovative machinery, providing greater flexibility in both quantities and types of raw materials compared to conventional methods.

Annex 3: Complementary data – alternative & novel ingredients

3.1. Canola

Anti-nutritional factors: Canola meal contains small amounts of heat-labile (glucosinolates) and heat-stable (phytic acid, phenolic compounds, tannins, saponins and fibre) ANFs. Currently produced canola meal contains very limited amounts of glucosinolates (3.2 µmol/g) and as most aquafeeds are produced today by extrusion, this factor is not limiting. The remaining ANFs in canola meal are consistent with those found in most plant materials, restricting the use of canola meal to 10-15% in tilapia feeds.

3.2. DDGS

Expressed as a percentage of the crude protein, DDGS is deficient in several essential amino acids, including lysine, threonine, tryptophan, arginine, isoleucine and phenylalanine, relative to SBM. Comparing the essential amino acids content of DDGS to the essential amino acids requirements of Nile tilapia, DDGS is severely deficient in lysine and to a lesser extent in methionine (Tridge, 2023).

DDGS is relatively palatable to fish, including tilapia. The inclusion of DDGS in the diet has been shown to increase feed intake in Nile tilapia (Lim et al, 2007). An increased fat level and the presence of distiller's solubles in diets containing DDGS might be responsible for these beneficial effects (Lim, 2010). Corn DDGS contains approximately 10% corn oil (table 18), which is a highly digestible energy source and it also contains approximately 58% linoleic acid (18:2n-6), which is an essential fatty acid for tilapia (NRC 2011).

Antibiotics, such as penicillin, virginiamycin, erythromycin and tylosin (tetracycline), might be used in the process of DDGS production to control the growth of bacteria during the fermentation process. The major concern is that these antibiotic residues might end up in animal feeds and potentially in fish tissues used for human consumption (Lim et al, 2011). Nevertheless, nowadays it is possible to source DDGS that is guaranteed to be antibiotic free.

Corn DDGS contains yellow pigments (xanthophylls) at a level of 15–25 ppm (Lim et al, 2011). These xanthophylls (mainly lutein, zeaxanthin and b-cryptoxanthin) might impart yellow pigment in fish skin and flesh (as shown for other fish species). Enhancing fish skin colour might be an advantage as the fish appears more attractive. No studies have been conducted on the effect of dietary levels of xanthophylls on tilapia fillet pigmentation.

3.3. Peanut Meal

Peanut meal (PM) serves as a protein-rich ingredient widely utilised in feeding various classes of livestock, including fish. The nutritional composition of PM exhibits variability depending on the production process, as outlined in Table 2A.

Table 2A: Average nutritional composition of 2 types of PM, as is basis (source: Fidipedia, https://www.feedipedia.org/node/699).

Product	Moisture (%)	Crude protein (%)	Crude fat (%)	Ash (%)	Fiber (%)	Carbohydrates (%)
Peanut meal mechanically extracted	7.7	45.3	9.0	5.3	6.4	26.3
Peanut meal solvent extract	9.6	48.2	1.9	6.2	6.4	27.7

Additionally, the composition may be influenced by the inclusion of shells and peanut skin along with the seeds before oil extraction. PM boasts a high protein content, ranging from 40-50%, comparable to soybean meal which may equally range from 40 to 50%. Notably, the essential amino acid profile in PM moderately aligns with most fish nutritional requirements, as indicated in Table 3A, with relatively lower levels of lysine, methionine, and tryptophan. Conversely, PM is a rich source of arginine, although this amino acid is generally not a limiting factor in fish nutrition. Protein digestibility appears variable, reaching 86.4% in barramundi fish (Vo et al., 2020) but only 77.6% in tilapia fish (Zhou and Yue, 2012).

Table 3A: Essential amino acid profile of 2 types of PM. the values are % of whole product, as is basis (source: Fidipedia, https://www.feedipedia.org/node/699).

Product	Arginine	Leucine	Histidine	Lysine	Methionine	Tryptophan	Threonine
Peanut meal mechanically extracted	5.1	2.6	1.0	1.6	0.5	0.3	1.1
Peanut meal solvent extract	5.4	2.8	1.1	1.7	0.5	0.3	1.2

Due to the diverse range of extraction processes, the oil content in PM varies significantly, ranging from less than 3% for solvent-extracted meals to 8-9% for mechanically extracted meals (Table 2A). The fatty acid composition of PM predominantly includes oleic acid (C18:1) at 56.3%, linoleic acid (C18:2) at 21.3%, and, together with palmitic acid (C16:0) at 12.3%, these three acids constitute 90% of the fatty acids in peanut oil(32). With this fatty acid profile, PM can be considered a valuable source of essential fatty acids for tilapia, despite its relatively low levels of linolenic acid (18:3).

The carbohydrate fraction in PM is approximately 25%, with the majority being starch. Substantial amounts of carbohydrates are removed during the oil extraction process. While the starch level is not high, PM may contribute to the binding properties of extruded pellets. Like other legume seeds, peanuts contain Anti-Nutritional Factors (ANFs), such as tannins, lectins, and trypsin inhibitors (Jithender et al., 2019). The ANFs tend to interfere with nutrient absorption and utilisation by the fed animal (fish inclusive). However, peanut lectins can be fully inactivated by heat, making peanut products safe for animal feeding under regular processing conditions. The presence of ANFs in PM is influenced by the inclusion of hulls and seed coats, with higher inclusion leading to more ANFs in PM.

The typical crude fibre level is 6.4%, higher than that in high-quality plant materials like soybean meal. In some instances, PM may contain up to 10% fibre particularly when there is significant inclusion of the skin and shell fragments.

Due to the toxicity and prevalence of aflatoxin contamination, most countries adhere to a maximum allowed limit of 20 ppb, following EU regulations (Commission directive 2003/100/EC). This stringent limit restricts the use of PM in fish feed, with many nutritionists preferring not to include it or limiting it to a maximum of 5% inclusion rate (personal information). Besides, feeds formulated with any proportion of PM must be dried to not above 10% moisture, to minimise fungal infestation.

In summary, PM contains a relatively high level of protein of intermediate quality and a high-quality lipid fraction. It contains relatively low levels of ANFs and those present are considered to be less deleterious relative to those in other legumes. However, the high risk of aflatoxin contamination limits its use in fish feeds. Furthermore, the level of inclusion in aquafeeds can be not more than 15% due to imbalances in essential amino acid profile, particularly low levels of lysine and methionine. Peanut meal has the potential to be a significant ingredient in tilapia feeds, but there is insufficient research on PM in tilapia feeds, and more studies are needed to address the amino acid imbalance and explore its potential in fish nutrition.

3.4. Sorghum

By 2016, 64% of sorghum in East and Southern Africa was used for human food, 11-14% of which being for brewing (Mwema et al., 2016; Orr et al., 2020), 3% for animal feed, and 19% for other non-food uses (Mwema et al., 2016).

The specific uses of sorghum can vary across countries and regions, but some common applications include: 1) direct use as human food usually in the form of porridge, flatbreads, and fermented products like injera; and/or as beverage in the production of alcoholic drinks like beer and spirits. 2) being a drought-resistant crop with adequate nutrients, sorghum is used in animal feeds in EA; 3) the high sugar content of sorghum makes it a viable source for ethanol production, as an alternative and renewable energy source. The growing demand for biofuel production, more so ethanol is envisaged to increase the demand for sorghum in EA; 4) sorghum is used in the production of starch, adhesives, and other bio-based products, offering economic opportunities for local farmers to price their product; hence, making it less available for feed formulation; 5) In many communities in EA, sorghum is used as a part of cultural practices and traditions. Taken together, the competing uses of sorghum consume substantial volumes of the grains, and lower the proportion available for feed formulation.

Nutrient composition of sorghum

Sorghum is among the most nutritious cereals farmed globally (Table 4A). However, the nutrient composition of sorghum tends to vary with varieties, farming conditions and geographical location. Evidently, sorghum is majorly a carbohydrate (67.6-80.0%), and less of a protein (8-18%) ingredient, that is rich in minerals (Table 4A).

Table 4A: nutrient composition of sorghum (Tanwar et al., 2023; Tasie & Gebreyes, 2020; Mwema et al., 2016)

Nutrient (Unit)	Content
Carbohydrate (%)	67.6-80.0
Moisture(%)	9.7-12.9
Ash(%)	1.1-2.3
Protein (%)	8-18
Lipids (%)	1-5
Crude fibre (%)	3 (2.2-8.6)
Calcium (mg/100 g)	9.6 - 67.2
Sodium (mg/100 g)	2.3 - 6.2
Potassium (µg/g)	2874
Magnesium (mg/100 g)	62.1-207.5
Phosphorus (mg/100 g)	112.6-367.1
Niacin (mg/100 g)	2.9
Riboflavin (mg/100 g)	0.14
Thiamin (mg/100 g)	0.24
Lysine (g/100 g protein)	2.0
Vitamin B-6 (mg/100 g)	0.59
Vitamin E (mg/100g)	0.81
Iron (mg/100g)	2.26 - 14.08
Zinc (mg/100g)	0.70 - 6.48

There are several varieties of sorghum, including; grain sorghum, sweet sorghum, forage sorghum and biomass or black sorghum, brown sorghum, yellow sorghum, red sorghum and white sorghum (Tanwar et al., 2023). The naming of sorghum varieties is inconsistent across the world; hence, the same variety can be named differently from country to country. In EA, the naming of sorghum varieties in Uganda (table 5A) completely differs from that in Kenya (table 6A) or Tanzania. In Uganda, the sorghum varieties are named as in Table 5A.

Table 5A: Agronomical characteristics of sorghum varieties in Uganda

Sorghum varieties	Days to maturity	Average grain yield (Kg/ha)	Grain colour	Unique attribute(s)
NAROSORG-1	110-120	3000-3200	Cream white	Medium maturity and excellent for brewing
NAROSORG-2	100-110	2700-3000	Red	Good for yeast and not much affected by birds
NAROSORG-3	110-120	3000	Chalky white	Midge resistant
NAROSORG-4	90-100	2300-2500	Brown	Good for food and not much affected by birds
SESO-1	90	3000	White	Early maturity and good for brewing
SESO-2	100	2500	White	Forage and resistant to lodging
SESO-3	95	3000	Brown	Good for food and not much affected by birds

Source: https://naads.or.ug/sorghum-varieties-grown-in-uganda. Retrieved on the 20th December, 2023.

Table 6A: Agronomic characteristics of sorghum varieties in Kenya

Sorghum varieties	Days to	Average grain yield (Kg/ha)	Grain colour	Unique attribute(s)
Serena	80-90	800-1,700	Smooth creamy brown seeds having a small eye	• Tolerant to yellow mottle virus and scab, moderately tolerant to septoria leaf spot and powdery mildew • Tolerance to aphids and thrips. • May mutate to various forms during the growing period.
Seredo	110-120	1000-2800	Brown with a testa and soft floury endosperm.	• It produces more outward spreading tillers and has thicker stems than Serena. • It is not cold tolerant and is cultivated in areas of 1300 to 1700 m above sea level.
KARI Mtama-1	95-100	2500	White with a hard endosperm and has no testa.	• It has one main erect tiller and sometimes has 2-3 straight tillers. • Highly tolerant to stalk borers and aphids. • Recovers from drought very fast. • Highly palatable and sweet making it attractive to birds.
Gadam	80 - 90	10	-	• Semi-dwarf small plants that grow to 100 – 130 cm tall, with a very uniform plant population. • Drought tolerant • Tolerant to stern borer and shoot fly.

Sorghum crops are categorised based on their use, such as for forage or grain. Grain sorghums are classified into three types according to their tannin contents: type I, that is tannins free while type II and III contain low and high levels of tannin, respectively (Zarei et al, 2022). In addition, Varietals are also grouped according to grain colour, e.g., black, brown, red, yellow, and white. Sorghum grain colour is indicative of several attributes, including nutrient levels and concentrations of ANFs, such as phenolic compounds and tannins. The correlation between grain colour and chemical composition is shown in Table 18. Red, orange, and bronze are the most commonly raised varieties and mostly used for animal feeding. All sorghum varieties are the result of conventional selective breeding and therefore are all GMO free (Zarei et al, 2022).

Sorghum, as a rich source of carbohydrates (table 18), is primarily used in aquafeeds as a contributor of starch for the extrusion process and as an energy source. The digestibility of the starch in sorghum is considered to be low, relatively to that of wheat and corn (Zarei et al, 2022). This might be explained as the starch in sorghum is bound in a protein matrix that limits the activity of digestive enzymes. Nevertheless, Sklan et al (2004) found the carbohydrate digestibility of sorghum by tilapia was 70.1%, that was comparable to that of wheat (71.7%) and superior over the carbohydrate digestibility of corn (57.9%). The discrepancies between the results of different researches might be explained by testing different sorghum varieties and probably because of different feed production methods. Technically, sorghum, as any other carbohydrate source, is used as a binder for pellet formation in the extrusion process. The starch gelatinisation temperature of sorghum is 68-76 degree C that is higher than that of corn and wheat; meaning that extrusion of sorghum containing feeds must be carried out in higher cooking temperatures, consuming more energy during the feed production process. Moreover, it has been claimed that pellets that contain sorghum in their formulation do not bind as well as pellets that contain corn (Feedipedia, 2023).

Sorghum's protein content falls between that of wheat and corn. Its amino acid composition varies with its protein content. Research has confirmed that sorghum grains contain relatively low levels of essential amino acids crucial for aquafeeds, including lysine, threonine, and total sulphur amino acids. The levels of these essential amino acids in sorghum are comparable to those in corn, with, for instance, lysine present at 0.2% in sorghum and 0.25% in corn (as is basis) (McCuistion et al, 2019). Since sorghum is primarily included in aquafeed formulations for its starch content, the practical significance of its amino acid composition in feed formulation is relatively limited. Furthermore, the total apparent digestibility of sorghum grain proteins is measured at 85.5%, surpassing corn proteins with an apparent protein digestibility of 75.1% (McCuistion et al, 2019).

Sorghum grains have a relatively low oil content, typically ranging from 2-3% (table 4A). The fatty acid composition of sorghum oil is as follows: linoleic acid at 52%, oleic acid at 32%, palmitic acid at 10%, stearic acid at 4%, and linolenic acid at 1% (Zarei et al, 2022). Given the limited total oil content in sorghum grains, its contribution to the dietary balance of essential fatty acids and energy in the feed is practically negligible.

As any other plant material, sorghum grains contain several ANFs. Sorghum grain might contain trypsin and amylase inhibitors, phenolic compounds, phytic acid, and tannins. These compounds are known to have a negative impact on protein, carbohydrate, and mineral metabolism in fish (Zarei et al, 2022). Tannins are the most potent ANF in sorghum, but as discussed previously in the clause, its concentration is related to sorghum variety (table 7A) and culture condition; therefore varieties with low amounts of ANF can be sourced by feed millers, to improve their feed quality.

Studies reporting about the dietary effect of sorghum in tilapia feeds are inconclusive, e.g. there are significant differences in nutrient digestibility. There are very few studies testing the effect of sorghum on growth parameters of tilapia. Al-Ogaily et al. (1996) tested the growth performance of tilapia Oreochromis niloticus (L.), fed diets containing different grain sources (maize, wheat, barley, sorghum and rice) at a level of 25%. Fish fed the diet containing sorghum had the highest weight gain, highest specific growth rate and the best feed conversion ratio compared to all other diets (Al-Ogaily et al. 1996).

In conclusion, Sorghum is well-suited for sustainable agriculture. It is drought-tolerant and thrives in a variety of climates, requiring fewer resources such as water and fertilisers and is less prone to fungal infections and mycotoxin contamination (Zarei et al, 2022). This aligns with the growing emphasis on eco-friendly and resource-efficient fish farming practices. There are several varieties of sorghum, not all of them fit for use in aquafeeds. However, selecting the right variety can be beneficial for aquafeed production. The existing data supports the safe utilisation of sorghum in tilapia feeds, allowing for up to 25% inclusion in the formula, making it a viable and competitive alternative to traditional grains in aquafeed, such as wheat and corn.

Table 7A: level of phytochemicals in varieties of sorghum based on grain colour (Zarei et al, 2022)

Grain colour	Phenolic compounds	Tannins
White tan varieties	Low levels	Absence
Yellow, red and black varieties	Modest and moderately high levels	Absence
Brown varieties contain high levels of tannins and are sometimes referred to as “tannin sorghums” [30].	High levels	High level

3.5. Black soldier fly (BSF)

BSF Nutritional content

The regulation of insect meal commenced a decade ago, with the European Union (EU) granting permission to use insect meal in aquafeeds in 2017 through regulation 2017/893. However, this regulation imposes restrictions on the feed sources for Black Soldier Fly (BSF) larvae, permitting only those of plant origin. Ruminant proteins, catering waste, meat-and-bone meals, and manure are explicitly excluded. This limitation significantly impacts production costs, as despite the biological capability of insects to digest a wide range of organic matter, the regulations restrict the use of the most cost-effective feed sources for larvae. It’s noteworthy that the regulatory status in the EA countries is currently unclear, and there may be differences that do not necessarily align with EU regulations.

Insects offer the distinct advantage of thriving on organic side-streams, making a significant contribution to a circular economy. BSF, for instance, exhibits the ability to bio-convert a diverse range of organic waste into nutrient-rich animal feeds. The efficiency of insect cultivation stems from their capacity to be grown in high densities, making it a land-efficient industry. Additionally, insect production requires minimal freshwater, generates minimal waste, and has low CO2 emissions.

Challenges:

1. Despite the nutritional and environmental benefits, there are challenges that need consideration:
2. Inconsistency in the nutritional profile of the BSFL. There are different types of organic waste utilised for BSF larvae culture which includes vegetable wastes, such as fruit wastes, grain wastes, human food wastes and different farm animal manure. Consequently, resulting in a variable nutritional content of BSF meal based on the organic waste materials consumed.
3. The production costs are notably high, especially in large-scale industrial production. As a result, global production remains limited, with an estimated annual production of

insect meal standing at 4,000 tons per year (at EU standards). This quantity is utilised in the production of approximately 10,000 tons of feed (IPIFF, 2023). Projections suggest that around 17,000 tons of insect meal will be produced in 2030 (Future ingredients for Norwegian salmon feed, 2022) Processing challenges when dealing with BSFL as it extrudes a large volume of liquid oil when post processing.

4. The ability of commercial manufacturers to secure regular quantities of BSFL in sufficient volumes. For example, one large BSFL manufacturer in Kenya can produce 0.3 MT of BSFL per month (KI, industry), which is far below the target production volumes of 4,200 tonnes per month of feed from a new feed miller in the region (KI, Industry).
5. Costs, as the cost to deliver processed BSFL in protein and fat format as a raw ingredient to feed manufacturers is still above conventional ingredients (KI, industry).

3.6. Duckweed

As a guide to investors, analysing how production costs vary with the scale of duckweed cultivation is crucial. Larger-scale operations may benefit from economies of scale, leading to lower production costs per unit of duckweed harvested and processed (Sarker et al., 2019; Song et al., 2020). Nevertheless, investors planning to invest in duckweed production and processing need to consider mapping out the likely market demand and the likely prices, if they are to make informed investment decisions. Like in other business enterprises, understanding the market dynamics is crucial for assessing the profitability of duckweed cultivation and processing (Chiaiese et al., 2020; Godfray et al., 2010), more so in EA where the practice is almost nonexistent. Being a new enterprise, duckweed production may have limited regulatory compliance requirements presently. However, investment should account for regulatory requirements and compliance costs likely to be associated with duckweed cultivation in the long run, including permits, licences, and environmental regulations (Ziegler et al., 2015; FAO, 2021). Currently, there is limited research and development on duckweed production and processing in EA. However, there is ongoing research and development efforts elsewhere, aimed at optimising duckweed cultivation techniques and reducing production costs over time (Bastidas-Oyanedel et al., 2019; Matassa et al., 2020), and this should be of interest to investors interested in duckweed production and processing.

Besides considerations related to nutritional content of duckweed, including protein, lipids, carbohydrates, vitamins, minerals and amino acids that is generally adequate for fish feed formulation (Costa-Pierce, 2002; Møller et al., 2019; Daudi, Luoga, & Hatiwa, 2020); several other factors need to be considered by investors and feed manufacturers intending to use duckweed. For example, the use of duckweed in fish feeds may be hindered by the high crude fibre content, and presence of metabolites like tannins, that are likely to affect its digestibility and utilisation by fish. Effective inclusion of duckweed in a diet is affected by the target fish species and life stage. The level of duckweed included in a diet affects palatability and acceptance of feeds by the target fish, suggesting that care must be taken during formulation to avoid excess inclusions that may lead to fish denying a diet. When included at a slightly high level, considerations to enhance acceptability are needed, such as adding attractants or fishmeal (Azim and Little, 2008; Chu et al., 2016). The presence of ANFs in duckweed and their potential effects on fish health and growth (Rusoff et al., 1980; Daudi et al., 2020) should be considered when duckweed is used in fish feeds. Anti-nutritional factors in duckweed tend to affect digestibility and nutrient utilisation by fish. Digestibility of duckweed by fish is generally low, majorly affected by the high fibre content and presence of ANFs (Naylor et al., 2009; Wang et al., 2016). Accordingly, to ensure efficient nutrient utilisation in duckweed-based diets and promote growth, feed formulators should regulate the levels of duckweed in fish diets. The optimal inclusion levels of duckweed in fish feeds must be guided by its nutritional composition, digestibility and the dietary requirements of the target fish species (Rahman et al., 2019; Hossain et al., 2021). Processing methods (e.g., drying, grinding) have been reported to affect the nutritional integrity of duckweed; hence, fish feed manufacturers are advised to explore those (methods) that preserve the nutritional integrity/value of duckweed (Nascimento et al., 2015; Møller et al., 2019). Although duckweed is rich in protein and other nutrients, with attributes close to those of animal ingredients (Hillman & Culley 1978; Journey et al. 1991; Bairagi et al. 2002; Yilmaz et al. 2004; Aslam et al. 2016; Asimi et al. 2018), feed manufacturers should consider the cost-effectiveness of using duckweed as a feed ingredient in fish feed, compared to conventional ingredients such as fishmeal or soybean meal (Bhujel, 2018; Nasir & Alam, 2020). Given its high moisture content, and low yield per unit of wet product processed, versus high cost of production, the unit cost of nutrients (e.g., protein) in Duckweed may be higher than that of fishmeal, soya and other conventional ingredients. Regarding environmental sustainability, duckweed cultivation and its potential effects on sustainable aquaculture practices is of concern (Hussain et al., 2019; Sarker et al., 2020). Ultimately, investors in duckweed production and fish feed manufacturers should be aware of the likely ecological and conservation challenges that may result from its massive production.

Effective investment in duckweed production should consider labour associated with planting, management, harvesting, maintenance, and processing. Labour costs in a duckweed farm set in EA is likely to depend mainly on the wage rates payable to humans, other than on mechanisation (Habib et al., 2014; Hussain et al., 2020); hence, the need to conduct thorough examination prior to establishment. The costs associated with setting up infrastructure (e.g., ponds, tanks, greenhouse) and acquiring equipment (e.g., pumps, aerators, harvesters) necessary for duckweed cultivation (Sarker et al., 2019; Li et al., 2020) must equally beassessed, because it can be outstandingly high. Expenses related to processing and harvesting duckweed, including drying, grinding, and packaging are crucial considerations for effective investment. Well planned, efficient processing methods can help minimize costs of duckweed (Yusoff et al., 2020; Nasir & Alam, 2020).

Annex 4: Consideration in feed ingredient selection

Proteins and fats are typically the most expensive nutrients that determine feed cost. Proteins within the feed should be used for fish growth and fats used for energy provision. Ensuring enough fat remains within the feed is therefore important to ensure protein is not being diverted to energy usage. Crude protein content of ingredients is the first nutrient feed formulators consider when creating a balanced and cost-effective diet that meets the specific protein requirements of fish, while promoting health and growth performance. Additionally, effectively balanced dietary crude protein plays a role in minimising the environmental impact of the formulated feeds. Crude protein content of the ingredients can be optimised to achieve compliance with regulations related to environmental pollution, feed floatation, fish growth, and economic and environmental sustainability of the fish farming enterprises. Therefore, the conventional and most routinely used ingredients in EA have been scored on crude protein and fat contents.

The unit cost of protein and energy of an ingredient is critical for feed formulators, because it is the major determinant of formulating cost-efficient diets that meet the nutritional requirements of fish while promoting profitability, regulatory compliance, and environmental sustainability. The unit cost of a given nutrient in an ingredient plays a significant role in optimising the economic and nutritional aspects of a formulated fish feed. For example, when two or more ingredients capable of providing the same nutrient are to be included in a formulation, unit protein cost is used to determine the most suitable ingredient.

Digestibility of ingredients provides information about the availability of essential nutrients, such as proteins, carbohydrates, fats, vitamins, and minerals, from the feed; hence, being essential for feed formulators. Apparent digestibility coefficient (ADC) helps feed formulators to calculate the actual nutrient content that will be absorbed and utilised by the fish. Knowledge of digestibility of ingredients allows formulators to tailor diets to meet specific requirements efficiently, ensuring that fish receive the right balance of nutrients for growth, production, and overall health, ADC of different ingredients is considered a key parameter in evaluating the quality of conventional ingredients. Moreover, digestibility impacts the growth performance and health of fish, feed cost effectiveness, and the extent of environmental pollution. Given that various factors affect ADC of ingredients, including; fish species, fish size, level of inclusion of that ingredient in the diet, protein and energy sources, lipids and carbohydrates levels; we considered ADC as an important factor in the choosing of ingredients that are suitable for Nile tilapia feed formulation.

Crude fibre affects the digestibility of an ingredient, and ultimately the utilisation of nutrients in a formulated feed. Therefore, the crude fibre content of an ingredient is an important score when evaluating the suitability of ingredients. Usually, the higher the fibre content, the lower is the digestibility of the nutrients in an ingredient. Therefore, crude fibre content of ingredients is essential for feed formulators when deciding on inclusion levels that can create balanced diets that meet the energy and nutritional needs of animals, while considering regulatory compliance, digestive health, cost efficiency, and environmental impact. Therefore, crude fibre content of an ingredient serves as a guide to feed formulators to make informed decisions about ingredient selection. Crude fibre content of an ingredient determines the inclusion levels of ingredients when formulating feeds for different fish species or fish of different sizes/ages. Accordingly, crude fibre has been used to evaluate the quality attributes of the conventional ingredients in this study.

Dry matter and ash content of the ingredients are equally important parameters, but they are less utilised in deciding inclusion levels of an ingredient in a formulation. Dry matter is important because it is used to consistently estimate the nutrient content of an ingredient. Ash reflects the inorganic mineral content of an ingredient, and these are usually required in minute levels in a formulation.

Annex 5: Sustainability considerations

Avoid additional pressure on agricultural resources

The demand for food, feed, biofuels and bio-based materials increases the pressure on agricultural land globally (Spiertz and Ewert, 2009; Godfray et al., 2010). In regards to livestock, the production of ruminants, such as sheep and cattle, puts pressure on grazing land, but the pressure on arable land (including resources such as freshwater and fertiliser) is driven by the increased production of non-ruminants, such as pigs and poultry (Galloway et al., 2007). Biodiversity loss is primarily driven by the global food production systems (Benton et al., 2021); and escalating impacts of climate change (FAO, 2018; Fry et al., 2016). Hence, for the EA member countries to become self-sufficient and be able to sustain their ambitious aquaculture production targets (mostly based on tilapia farming), the impacts of climate change and increased aquafeed ingredients production must be considered. Accordingly, a comprehensive approach that considers resource conservation and environmental impact perspectives is crucial. In the following sections we briefly summarise the most important agricultural resources to consider. In addition, to the evaluation of the nutritional and environmental potential of these crops and derived ingredients, processing, and refining methods (e.g., reducing ANFs and other contaminants) should be separately assessed (Albrektsen et al., 2022).

Land

Estimates from the last decade, highlighted that 91% (4.9 billion ha, equal to approximately 40% of total global land surface) of the total 5.41 billion ha of available suitable agricultural land is occupied (incl. pasture) (Zabel, Putzenlechner and Mauser, 2014; FAO, 2014; Popp et al., 2017). If pastures and animal feed production is considered, it is estimated that 77% of agricultural land area is used for livestock (Ritchie and Roser, 2019). Consequently, indicating that horizontal agricultural expansion is limited and mostly at the expense of other land use (e.g., forest or protected areas) with social and environmental implications (Zabel, Putzenlechner and Mauser, 2014).

Agricultural production to satisfy the global demand for aquafeed ingredients, such as rapeseed, soybean, corn, nuts and wheat, was estimated at 10 million ha (approx. the size of Iceland in 2008) (Fry et al., 2016). Regarding feed production in EA, it is crucial to prioritise local production that does not compete significantly with other agricultural crop production and their respective resources, such as land, freshwater and fertiliser as explained in the following sections. In addition, production in harmony with nature should be prioritised to protect natural areas and natural areas that EA has to offer, as well as the tourist industry. It is important to explore affordable and available feed ingredients with nutritional potential, preferably locally or regionally produced, while having a minimal impact on the marine and terrestrial ecosystem.

The human population in EA is estimated at 102 million, while the domestic animal population is estimated at 1.4 billion, both sharing a supply of approximately 17 MMT of plant-based ingredients (mostly, maize, wheat, sunflower seed, cotton seed, and peanut) for food/feed (FAO, 2021). These ingredients are harvested from about 15 million ha of land which is about 53% of the arable land (27 million ha). With the annual average human population growth rate of 2.6%, and animal population growth rate of 3.95%, human and animal population are estimated at 221 million and 4.3 billion in 30 years (2053), respectively. This will translate into increased human population density from the present 60.9 persons per km 2 to about 132 persons per km2; creating a potential encroachment to agricultural land by settlement. Meanwhile, the demand for arable land area is expected to increase at 1.33% p.a; hence, changing from the present 27 million ha to an estimated 41 million ha in the next 30 years. Practically however, access to arable land is increasingly becoming difficult following population increase, land fragmentation, urbanisation and industrialisation. Therefore, the reliable mechanisms to increase crop productivity remains fertilisation or use of high yielding varieties, several of which are GMOs being contested in EA. It is estimated that 36 MMT of plant-based ingredients will be needed to support the human and animal population in the EA by 2053.

Water

Agriculture activities are also responsible for use of 70% of the freshwater resources, potentially leading to water scarcity in the future (Salin et al., 2018). Freshwater volumes to satisfy the demand for global aquafeed ingredients was estimated between 31–35 km3 (Pahlow et al., 2015). In order to increase water efficiency, arid regions such as Kenya and Tanzania would benefit from crops not requiring large volumes of water. Contrary, water demanding crops might be better suited to the wetter and more humid areas of Uganda and Rwanda. In both cases, crops could benefit from irrigation, which could improve the water efficiency, as water could be applied in small quantities, but on a regular basis, which can improve uptake and crop yields as well. Such systems combined with 3R (Recharge, Retention and Reuse of groundwater & rainwater) could enhance the resilience of agriculture production systems by enhancing sustainable water management. Consequently, increasing the availability of water for local use and agriculture and therefore enhancing the resilience of farming communities against floods, droughts and climate change (3R, 2023).

Fertiliser

Phosphorus is an important nutrient for agriculture production, but in limited supply (Ytrestøyl, Aas and Åsgård, 2015; Roy et al., 2016; Kraan, 2010), while combined with nitrogen in fertilisers could potentially lead to eutrophication of waterbodies in particular coastal marine ecosystems (Pelletier et al., 2018; Kraan, 2010; Diaz and Rosenberg, 2008). It is important to consider the potential implications of fertiliser dependency and stimulate regional production. For example, the global fertiliser market was disrupted significantly by covid followed up by Russia's invasion of Ukraine, as well as by the increasing prices for energy (IFPRI, 2023).

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