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RECENT ADVANCES, CHALLENGES, OPPORTUNITIES, PRODUCT DEVELOPMENT AND SUSTAINABILITY OF MAIN AGRICULTURAL WASTES FOR THE AQUACULTURE FEED INDUSTRY – A REVIEW

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Abstract

Million tonnes of agricultural waste are generated annually worldwide. Agricultural wastes possess similar profiles to the main products but are lower in quality. Managing these agricultural wastes is costly and requires strict regulation to minimise environmental stress. Thus, these by-products could be repurposed for industrial use, such as alternative resources for aquafeed to reduce reliance on fish meal and soybean meal, fertilisers to enrich medium for growing live feed, antimicrobial agents, and immunostimulatory enhancers. Furthermore, utilising agricultural wastes and other products can help mitigate the existing environmental and economic dilemmas. Therefore, transforming these agricultural wastes into valuable products helps sustain the agricultural industry, minimises environmental impacts, and benefits industry players. Aquaculture is an important sector to supply affordable protein sources for billions worldwide. Thus, it is essential to explore inexpensive and sustainable resources to enhance aquaculture production and minimise environmental and public health impacts. Additionally, researchers and farmers need to understand the elements involved in new product development, particularly the production of novel innovations, to provide the highest quality products for consumers. In summary, agriculture waste is a valuable resource for the aquafeed industry that depends on several factors: formulation, costing, supply, feed treatment and nutritional value.

Key words: aquaculture feed, plant-based protein, animal-based protein, immunostimulator, protein replacement, environmental stress, sustainability

Agricultural waste refers to residues resulting from various agricultural activities, such as the production and processing of plantation crops, livestock, fruits and vegetable farming (Kari et al., 2020; Ramírez-García et al., 2019). The agricultural industry continues to expand in tandem with the increasing global human population and food demand, hence the increase in agricultural waste. The agricultural waste covers between 0.5% and 50% of production, depending on the agricultural activity and the plant processing management. Therefore, agricultural waste will be a liability to the environment, economy, and human health without proper waste management plans and actions. In addition, agricultural waste is highly nutritious but not fit for human consumption (Ajila et al., 2012). Therefore, repurposing or transforming waste into functional forms, such as animal feed, is a sustainable alternative for agricultural waste management.

Over the last 20 years, many animal feed manufacturers and researchers have begun incorporating agricultural waste into their feed formulations to save costs (Van Doan et al., 2021). For instance, rice bran is used in poultry feed, while palm kernel cake is used in ruminant feed. Meanwhile, agricultural waste is incorporated into aquafeed ingredients for effective production cost, waste management, and industrial sustainability. The aquaculture industry has been relying on fish meal (FM) as farmed fish feed for years, but the option is no longer economically viable or environmental practical due to the depleting natural resources. Apart from that, FM has long been a highly sought-after ingredient for aquafeed, farm animal feed and pet food, resulting in the skyrocketing commodity price (Frempong et al., 2019; Galkanda-Arachchige et al., 2020). Therefore, substituting FM with alternative ingredients, such as agricultural waste, is one of many ways to sustain the aquaculture industry. Aquafeed is of low priority in the animal feed industry for various reasons: 1) The dominance of poultry and ruminant farms in the world food supply; 2) The ability of terrestrial animals to better utilise plant-based sources than aquatic animals. Despite the limited success in incorporating agricultural waste into aquafeed, this alternative remains viable as studies have reported favourable results. Therefore, agricultural waste inclusion in aquafeed is expected to become a mainstay in the near future.

Aquaculture and sustainability

Fish is a cheap and primary protein source for more than 1 billion people worldwide (Omojowo and Omojasola, 2013). The total live weight of the world aquaculture production was 114.5 million in 2018 (FAO, 2020). As the aquaculture business intensifies to meet the global fish demand, the benefits and drawbacks of these activities are increasingly recognised. For example, echinoderms, bivalves, and seaweed farming are economically viable and environmentally friendly. It has been reported that *Kappaphycus* spp. seaweed farming can help reduce open sea acidification by utilising nutrients and maintaining good water quality for other aquatic life (Garland, 2021). Seaweed is also a source of valuable compounds such as carrageenan, which are beneficial as food, beverages and healthcare. Furthermore, detritus consumption by sea cucumbers can aid in seafloor cleanup. The increasing sea cucumber production can also cater to the growing demand for seafood, particularly in Asia.

One of the main reasons for the rising environmental concerns is the high dependency of the aquaculture industry on the fish meal as the primary protein source in aquafeed formulation (Sprague et al., 2016). Despite decades of research on alternative ingredients that can replace FM, total replacement of this gold standard ingredient is impossible due to practicality and feasibility issues (Turchini et al., 2019). For instance, the formulation of salmon aquafeed requires a significant amount of FM. The amount of FM used in salmon farming has decreased significantly over the years (from 4.4 kg to 0.7 kg of FM to produce 1 kg of fish), and the inclusion of FM in the dietary formulation remains critical (Ytrestøyl et al., 2015). In addition, extensive studies have been conducted to reduce the fish in/fish out (FIFO) value by using alternative ingredients such as insect meal and agricultural waste.

Global scenario and trend of agricultural waste

Million tonnes of agricultural waste are generated annually due to the cultivation and processing of crops, fruits, and animals (Ytrestøyl et al., 2015). The total agricultural waste from main producer countries was estimated to be 60 million tonnes of wheat bran, 150 million tonnes of soy pulp, 45 million tonnes of rice bran and 200 million tonnes of palm kernel cake. These wastes are generated by all types of agricultural activities at different phases. Figure 1 illustrates the estimated global major agricultural (crop) waste products in 2020. Besides proper management, most agricultural wastes contain nutrients essential for aquaculture.

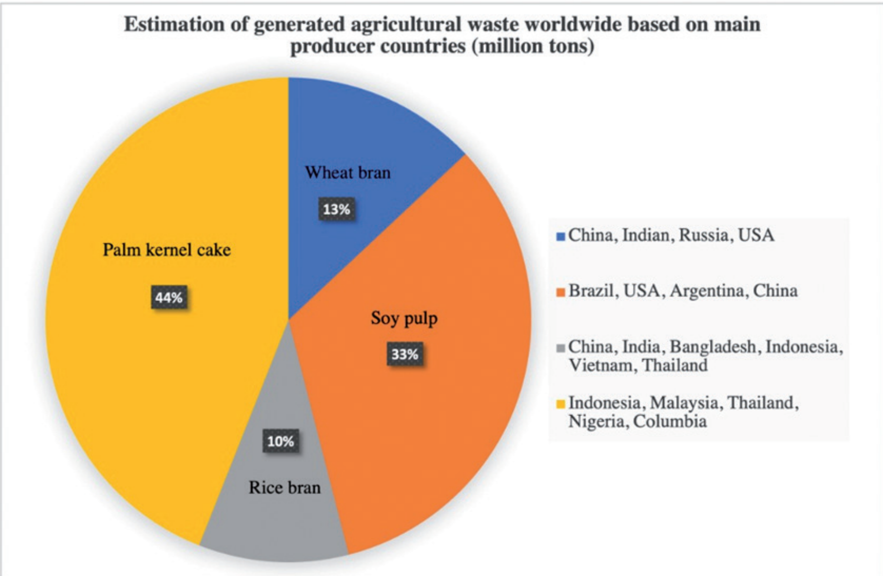

Figure 1. Global production of the leading agricultural products and estimated potential agricultural wastes production in 2020; Source: FAO (FAO, 2021)

Table 1. Recent studies on aquaculture species fed with agricultural waste diets

Agriculture waste	Aquaculture species	Dose	Time	Findings	References
Fermented rice bran	Pacific White shrimp, *Penaeus vannamei*	50% fermented rice bran + 50% commercial probiotic	Four weeks	Reduced pathogenic bacteria in the shrimp culture system	Liñan-Vidriales et al., 2021
Fermented soy pulp	African catfish, *Clarias gariepinus*	50% of FM replacement in the diet	Eight weeks	Enhanced the growth and health status of fish; Improved protein digestibility of the fish and increased essential amino acid profile in the fish muscle	Kari et al., 2022 b; Kari et al., 2021
Molasses	Whiteleg shrimp, *Litopenaeus vannamei*	Molasses combined with corn starch (2 molasses: 1 corn starch)	Five weeks	Enhanced growth performance of whiteleg shrimp	Tinh et al., 2021
	African catfish	Molasses addition based on C:N ratio 10 :20	30 days	Enhanced growth performance of catfish and maintained good water quality	Rahmatullah and Rahardja, 2020
Carica papaya leaf extract	Red hybrid tilapia, *Oreochromis mossambicus* × *Oreochromis niloticus*	Replacement of 1% and 2%	12 weeks	Promoted fish growth	Hamid et al., 2022
Pineapple waste	Nile tilapia, *O. niloticus*	50% of replacement with FM	Eight weeks	Improved growth conditions	Sukri et al., 2022
Germinated peanut meal	Barramundi, *L. calcarifer*	Replacement of 15% FM	Eight weeks	Cost effective	Vo et al., 2020
Palm Oil Mill Effluent (POME)	Rotifer, *Brachionus rotundiformis* (live feed)	POME combined with photobacterium at biomass 2.58 ppt	Six days	As fertiliser to grow live feed	Poh-Leong et al., 2012
Palm kernel cake (PKC)	Juvenile rohu, *Labeo rohita*	Replacement of 10% FM	60 days	Cost-effective	Sangavi et al., 2020
Olive leaf	Nile tilapia, *O. niloticus*	1% in feed	Two months	Enhanced the growth and health status of fish	Fazio et al., 2022
Olive waste	Rainbow trout, *Oncorhynchus mykiss*	2.5 g olive waste per kg of fish	Six weeks	Enhanced the growth of the fish	Hoseinifar et al., 2020
Banana peel flour	Rohu, *L. rohita*	5% of feed weight	60 days	Enhanced the health status of fish	Giri et al., 2016
Orange peel	Gilthead seabream, *Sparus aurata* L.	2.9 to 5.5 ppm of fish weight	60 days	Enhanced the health status of fish	Salem et al., 2019
Yeast-fermented poultry by-product meal (PPM)	Nile tilapia, *O. niloticus*	11.17–25.14% as a protein source	Eight weeks	Alternative protein source	Dawood and Koshio, 2020
Fermented chicken manure (FCM)	Nile tilapia, *O. niloticus*	25% (FCM) + 75% commercial feed	60 days	Alternative feed	Elsaidy et al., 2015
Pig manure	Nile tilapia, *O. niloticus*	15% replacement of FM	120 days	Alternative protein source	Tongmee et al., 2020

The application of agricultural waste for aquafeed and aquaculture practices

Agricultural crops include grain, oil-barrier plants, legumes, vegetables and fruits. Meanwhile, agricultural animals refer to poultry, ruminants, aquaculture, and fisheries. The agricultural wastes comprise farm or field residues, processing and industrial waste from the agricultural sector (Agrawal et al., 2018). Farm or field residues are waste produced directly at the field, such as the leaf, stalk, seed and stem of the plant, and solid waste of farmed animals. Processing residuals refer to waste from the processing facility, such as husks and bran from grain mills, molasses from sugarcane processing, and blood and mucus from abattoirs. Industrial residues are by-products of the processing of food products before reaching store shelves. In addition, fruit peels, okara, palm kernel cake, rendered fat, and bone meal are by-products of the food processing industry. To date, all types of agricultural waste have been incorporated in aquafeed depending on suitability. Table 1 presents recent aquaculture studies, where various species are provided with agricultural waste diets. The agricultural waste can be used for replacement, inclusion or additive in the fish diet (see Figure 2).

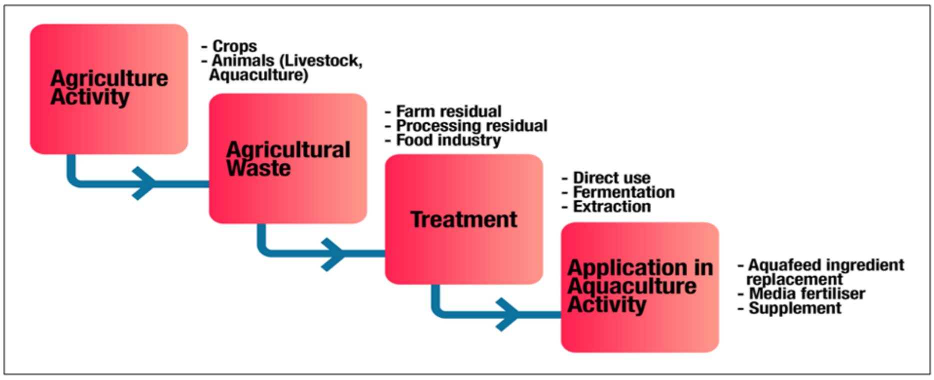

Figure 2. Overview of the sustainability of agricultural waste in aquaculture activities

Overview of the sustainability of agricultural waste in aquaculture activities

Crop agricultural waste

Rice bran

Rice bran is a by-product of rice production. A total of 63 million tonnes of rice bran are produced annually worldwide and primarily used as animal feed (Webber et al., 2014). Rice bran contains about 17% lipid, 12% protein, 7% ash, 28% fibre and 50% carbohydrate (Choi et al., 2011; Khir et al., 2019). Rice bran has a good nutritional profile, making it a highly sought-after ingredient for poultry and ruminant feed, and aquafeed. In aquaculture, rice bran is also used to fertilise water in the aquaculture system, apart from being included in the feed formulation. For instance, Limbu et al. (2016) evaluated the potential of rice bran as a sole tilapia feed in a semi-intensive system. It was reported that rice bran (single ingredient) produced a similar fish yield as those fed with mixed diets. Furthermore, rice bran usage as an aquafeed was enhanced via fermentation. Liñan-Vidriales et al. (2021) reported feeding Pacific white shrimp, *Penaeus vannamei*, and commercial feed combined with fermented rice bran improved shrimp production. In another study, fermented rice bran enhanced the growth and survival rate of tilapia, *Oreochromis niloticus* (Muaddama and Putri, 2021). Likewise, Romano et al. (2018) discovered that the fermented rice bran application via biofloc technology in African catfish, *Clarias gariepinus*, farming showed promising results in maintaining good water quality and promoting fish growth and survival rate. Fermented rice bran via biofloc technology is also beneficial in white leg shrimp, *Litopenaeus vannamei*, culture (Abdel-Tawwab et al., 2020). Moreover, Yanto et al. (2018) highlighted using fermented rice bran as a probiotic promoter in jelawat *Leptobarbus hoevenii* farming.

Wheat bran

Wheat bran is a fibre-rich by-product from wheat flour mill production (Wieser et al., 2020). Raw wheat bran is composed of 16% protein, 5% lipid, 6% ash, 12% carbohydrate and 43% fibre (Yan et al., 2015). Wheat bran is rarely used in fish feed due to the high fibre content. Initially, the utilisation of wheat bran in fish feed was conducted by Hilton and Slinger (1983) on rainbow trout. It was reported that middling wheat replacement using wheat bran improved the growth and body indices of the experimental fish. In recent years, the fermentation technique was employed as a pre-treatment for wheat bran to degrade the fibre structure and increase the protein content (Pangestika and Putra, 2020). The use of fermented wheat bran in Nile tilapia, *O. niloticus*, diet improved their growth performance (Pangestika and Putra, 2020). To date, the research on wheat bran utilisation in aquaculture remains limited, but earlier research demonstrated the potential of wheat bran as a raw material in fish feed formulation. Furthermore, fermented wheat bran performs better than non-fermented wheat bran.

Soy pulp/Okara

Soy pulp, also known as okara, is a by-product of the soy milking industry. Soybeans are legumes with a high protein content that bind nitrogen from the soil. Despite the high protein loss during the milk pressing process, the soy pulp still contains a high protein concentration (± 25%) (Li et al., 2012). Okara is ideal and widely used as feed for livestock as a supplemental protein source and plant fertiliser due to the high fibre content (>50%) (Li et al., 2012; Rahman et al., 2021). Furthermore, fermentation can boost the nutritional value of soy pulp by reducing the fibre content and increasing the protein level. A study showed that dietary fermented soy pulp could be increased by up to 50% without adverse effects on African catfish, besides improving their general health (Kari et al., 2021). In addition, Kari et al. (2022 a) found that 50% replacement of FM with fermented soy pulp enhanced the protein digestibility in fish and increased the essential amino acid profile in their muscles. Moreover, utilising soy pulp (10 to 20%) as a FM replacement in Pacific white shrimp, *Litopenaeus vannamei*, improved their growth performance without negative impacts (Forster et al., 2010). In summary, soy pulp is a high potential protein source in fish feed formulation but outperformed by fermented soy pulp in FM replacement rate.

Peanut (groundnut) meal

Peanut meal or peanut by-products are produced from industrial peanut oil extraction (Sorita et al., 2020; Zhao et al., 2012). This waste contains approximately 45% protein and <10% fibre (Batal et al., 2005), and is widely used for livestock, including aquaculture. Based on the literature, peanut meal can be included in fish feed formulations at a specific dosage to avoid adverse effects on their growth. The application of peanut meal to replace expensive ingredients such as soy meal and FM significantly reduced the cost of feed formulation. For instance, peanut meal replaced FM in a hybrid grouper diet by up to 50% without adversely affecting fish growth (Ye et al., 2020). Nevertheless, the diet replacement resulted in the increment of pathogenic bacteria in the hybrid grouper's intestine (Ye et al., 2020). In a different study, Li and colleagues suggested that peanut meal is a suitable soybean meal replacement in channel catfish diets up to 25% without any adverse effects on fish growth (Li et al., 2018).

Olapade and George (2019) suggested that defatted peanut meal is suitable as a FM replacement of up to 50% for catfish feed formulation without any adverse effect on fish growth, while maintaining water quality. Other studies that evaluated the potential of peanut meal in aquaculture with positive responses include Xu et al. (2012) in Pacific white shrimp, *Litopenaeus vannamei*, Yıldırım et al. (2014) in Mozambique tilapia fries, *Oreochromis mossambicus* and Vo et al. (2020) in juveniles of barramundi, *Lates calcarifer*. Furthermore, peanut meal blend can replace up to 60% of soybean meal in Yellow River carp without harming fish growth (Wang et al., 2020).

Molasses

Molasses is a by-product of sugar production. This thick and brown syrup was widely used in food, beverage, and health supplements due to the high nutritional value, abundance and low cost. Therefore, molasses is widely used in animal farming, including in aquaculture. A recent study by Tinh et al. (2021) stated that molasses combined with corn starch promoted the growth of whiteleg shrimp, *Litopenaeus vannamei*, in a biofloc system by increasing the biofloc yield, hence more feed for the aquaculture species. Furthermore, molasses added into *L. vannamei* farming system improved shrimp production and water quality compared to the system with rice bran and dextrose (Serra et al., 2015). Thus, molasses helps control water quality while boosting shrimp production.

Molasses can also remove and degrade aquaculture wastewater by contributing external carbon sources promoting aerobic denitrification in an aquaculture system (Tong et al., 2019). Furthermore, the presence of molasses in an aquaculture system can stimulate and increase denitrifying bacteria such as *Pseudomonas*, *Comamonas* and *Zoogloea*, thus enhancing waste removal in an aquaculture system. Similarly, Samocha et al. (2007) found that adding molasses into the grow-out system of *L. vannamei* helped control water quality by reducing total ammonia nitrogen (TAN) in the system. Moreover, Willett and Morrison (2006) agreed that molasses at appropriate concentrations could help reduce TAN in an aquaculture system by providing carbon sources for the blooming of the denitrifying bacteria. Likewise, several studies have reported the impact of molasses in controlling water quality by reducing TAN in aquaculture systems, such as Schneider et al. (2006), Panjaitan (2010), De Souza et al. (2014), Pantjara et al. (2013), Duy and Van Khanh (2018), and Rahmatullah and Rahardja (2020). In conclusion, molasses can be used as a wastewater bioremediation agent in aquaculture systems.

Palm oil by-product: Palm oil mill effluent (POME)

Oil palm is an oil-bearing plant. In the refinery, palm oil mill effluent (POME) is the wastewater produced during palm oil processing (Poh et al., 2010). This effluent can be harmful to the environment if untreated before being discharged into the environment because of the high biological oxygen demand (BOD) and chemical oxygen demand (COD) (Aziz et al., 2020). Despite being a non-toxic effluent, POME high nutrient content will result in eutrophication, eventually eradicating aquatic life in the ecosystem if not properly managed. Muliari et al. (2020) found that POME is harmful to aquatic animals, particularly in the early stages, because POME compromises the egg-hatching and larvae survival rate of Nile tilapia, *O. niloticus*. In addition, a high concentration of POME will lead to high malformation and abnormal heart rate in the fish larvae. Numerous studies were performed to repurpose POME. For example, Poh-Leong et al. (2012) found that POME is a suitable medium for the phototrophic bacterium, *Rhodovulum sulfidophilum* culture. The combination medium is known as POME-PB and is used as feed for rotifer, *Brachionus rotundiformis*, and live feed for larvae of marble goby, *Oxyeleotris marmorata*, yielding positive results. Furthermore, Habib et al. (1997) revealed the potential of POME as a fertiliser to propagate live feed for aquaculture. In the study, POME can be used as a medium to propagate microalgae, *Chlorella vulgaris*, and grow chironomid larvae effectively. Both live feeds are highly nutritious feed for aquaculture species larvae.

Palm oil by-product: Palm kernel cake (PKC)

Palm kernel cake (PKC) is a substrate derived from palm oil extraction. This by-product is rich in protein and fat and commonly used in the livestock feed industry. Several studies have evaluated the potential of PKC as a protein source in fish feed formulation (Ng and Chen, 2002). For instance, Sukasem and Ruangsri (2007) claimed that PKC is a promising protein source for red tilapia, *Oreochromis* spp., and feed formulation at 15% to 45% inclusion without compromising the fish growth and health. Nevertheless, >45% PKC in tilapia feed formulation can lead to steosis in fish. Likewise, Ng and Chen (2002) reported adverse effects in catfish that received 40% of PKC feed formulation. Meanwhile, there was no difference in the growth performance of catfish receiving <40% of PKC feed formulation compared to the control group fed with commercial feed containing soybean meal. In addition, Sangavi et al. (2020) showed that 0.26 to 10% PKC inclusion promoted the growth of juvenile rohu, *Labeo rohita* without compromising the fish growth performance. Iluyemi et al. (2010) fermented PKC to reduce the fat content before including the ingredient in red tilapia feed formulation. At the end of the experiment, it was found that higher fermented PKC inclusion in the feed led to a decrease in red tilapia weight gain. Therefore, it can be concluded that PKC can be included as protein and fat sources in fish feed formulation but not at high percentages, which may be detrimental to fish health.

Olive oil by-products

The olive oil, *Olea europaea*, industry produces high amounts of by-products. Olive oil wastes included leaf (5% of the weight of the olive in oil extraction), 35 kg of crude olive cake per 100 kg olives, and 100 litres of oil mill wastewater per 100 kg olives (Alcaide and Nefzaoui, 1996; Hazreen Nita et al., 2022). This oldest cultivated crop (Kapellakis et al., 2008) is widely used in food, beverage and traditional medicine (Acar-Tek and Ağagündüz, 2020). Recent study findings suggest that olive oil by-products are useful in managing aquaculture species' health. Various studies have revealed the potential of these wastes for aquaculture uses. For example, Hoseinifar et al. (2020) claimed that olive waste incorporated with feed (2.5 g olive waste per kg of fish) in a six-week feeding trial enhanced the growth of rainbow trout, *O. mykiss*. Meanwhile, Fazio et al. (2022) discovered that olive leaf extract added to fish feed at 1% improved the growth performance and health states of Nile tilapia, *O. niloticus*. Besides fish, the olive leaf extract is useful for shrimp health management. Gholamhosseini et al. (2020) reported that methanolic olive leaf extract is useful against white spot virus syndrome in *P. vannamei*. The extract was mixed with the feed and fed to the shrimp for two weeks before exposing them to viral-medicated feed. The shrimp exhibited resistance towards the virus at the end of the experiment.

Vegetables and fruits waste

Fruit processing wastes and products were estimated to be approximately 100 million tonnes, and management has become challenging for industrial players (Fierascu et al., 2020; Marić et al., 2018). Studies have shown that fruit processing wastes and by-products are promising supplements for aquaculture species due to the presence of bioactive compounds and exogenous enzymes (Dawood et al., 2022; Habotta et al., 2022). For instance, banana peel flour incorporated with fish feed 5% promoted the health of rohu, *L. rohita* (Giri et al., 2016). Meanwhile, Salem et al. (2019) claimed that orange peel fed to gilthead seabream, *Sparus aurata*, at 2.9 to 5.5 ppm of fish weight for 60 consecutive days helped maintain good fish health. Chinese yam peel, a fruit processing by-product, contains properties that could eliminate pathogenic bacteria in fish intestines by increasing beneficial microbiota in their digestive system. Similarly, Meng et al. (2019) claimed that a bioactive compound in the Chinese yam peel, known as the yam polysaccharide, promoted good microbial growth while eliminating pathogenic bacteria, such as *Vibrio* and *Pseudomonas*. In addition, the pineapple crown, skin and core contain bromelain, a proteolytic enzyme that improves digestion and the immune system in tilapia (Sukri et al., 2021; Van Doan et al., 2021; Yuangsoi et al., 2018). Papaya plant waste contains papain, a proteolytic enzyme found only in *Papaya carica*. Several studies demonstrated that papaya waste extracts such as leaf, skin, and seed improved growth performance and blood parameters in various fish species (Kareem et al., 2016; Olmoss, 2012; Olusola and Nwokike, 2018; Sukri et al., 2021).

Animal-based by-products

Blood meal

Blood meal is the purified blood of slaughtered animals collected from the abattoir and animal processing plants, containing approximately 90% protein, 3% lipid and 4% ash (Do Carmo Gominho-Rosa et al., 2015). Furthermore, this high-quality protein meal possesses an excellent essential amino acid profile except for isoleucine. Despite the imbalance in the amino acid profile, studies in Nile tilapia showed that blood meal could replace up to 50% of dietary FM without causing adverse effects (Montoya-Camacho et al., 2019). FM replacement using blood meal has also been studied in other species, such as red hybrid tilapia (Fasakin et al., 2005), palmetto bass (Gallagher and LaDouceur, 1996), African catfish (Ogunji and Iheanacho, 2021; Ogunji et al., 2020), rohu (Hussain et al., 2011), rainbow trout (Bahrevar and Faghani-Langroudi, 2015), channel catfish (Mohsen and Lovell, 1990) and white shrimp (Ye et al., 2011). Nonetheless, the response of other fish species towards the inclusion of blood meal is different to that of Nile tilapia. In most reports, blood meal is only beneficial at a low inclusion level.

Poultry by-product meal (PPM)

Poultry by-product meal (PPM) is a feed ingredient made from wastes obtained from poultry slaughterhouses and processing plants. There are two types of PPM commonly used for animal or fish feed: poultry offal meal (POM) and feather meal. Numerous studies have evaluated the potential of PPM in replacing FM in freshwater fish, marine fish and crustacean feed formulation (Galkanda-Arachchige et al., 2020). Poultry offal meal, for example, has been evaluated in many fish species, and among those that have been studied were silver seabream (El-Sayed, 1994), Atlantic salmon (Rocker et al., 2021), humpback grouper (Shapawi et al., 2007), seabass (Siddik et al., 2019), African catfish (El-Husseiny et al., 2018). Feather meal: gilthead seabream (Al-Souti et al., 2019; Psofakis et al., 2020), tilapia (Alves et al., 2019; Poolsawat et al., 2021) and giant croaker (Wu et al., 2018). Galkanda-Arachchige et al. (2020), in their review report, mentioned that the substitution of FM with PPM in aquaculture feed is promising in shrimp compared to marine and freshwater fish. At the same time, marine fish performed better feed conversion rates (FCR) than freshwater fish by using PPM in feed formulation (Galkanda-Arachchige et al., 2020; Ghosh et al., 2022). Srour et al. (2016) reported that PPM could replace FM as high as 40% without any compromising to the growth performance of marine fish European seabass, *Dicentrarchus labrax*, fry. However, Chaklader et al. (2020) found that total replacement of FM with PPM negatively affected the growth performance of juvenile barramundi, *Lates calcarifer*. However, combination of insect meal and PPM in feed formulation to totally replace plant-based protein source was found promising in gilthead seabream, *Sparus aurata* (Randazzo et al., 2021). Total replacement of PPM in feed formulation for freshwater fish is not promising. For instance, Dawood et al. (2020) reported that fermented PPM alone can be used as low as 11.17 to 25.14% as protein source in Nile tilapia, *Oreochromis niloticus*, feed formulation in order to avoid adverse effect to the growth performance of the fish and to maintain the fish health. Fermented feather meal in tiger shrimp and silver pompano, treated feather meal for largemouth bass (Ren et al., 2020) and enzymatic treated PFM on rainbow trout (Pfeuti et al., 2019).

Fish processing wastes

Fish products will be processed before selling into the market. Almost 70% of fish products will be processed (grading, beheading, scaling, gutting, fins cutting, bone separation, steak and fillets) and produce considerable waste (Ghaly et al., 2013). This waste is known as fish processing waste. Not all fish processing wastes can be processed into FM for aquaculture feed formulation. The market rejected whole or low-quality fish, which will be transformed into FM for pig feed, poultry feed, and aqua feed (FAO, 2012). Besides FM, other fish processing wastes such as skin, bone and shellfish wastes (shrimp head, appendages and exoskeleton) are also nutritious (Afreen and Ucak, 2020), hence suitable for aquafeed formulation. Fish skin is rich in gelatine and collagen (Afreen and Ucak, 2020), fish bone is a good source of antioxidants (Morimura et al., 2002), and shellfish wastes are rich in methionine and lysine (Fanimo et al., 2000). Nonetheless, FM remains the highly-sorted fish processing waste for aquaculture and other animal feed. Therefore, more studies need to explore other fish processing wastes as potential raw materials for aquaculture feed formulation in the near future.

Chicken manure

Chicken manure is commonly used in extensive and semi-intensive aquaculture systems. This poultry by-product is used as a fertiliser to propagate microalgae, a primary feed for zooplankton in an aquaculture system. Zooplankton is the primary source of live feed for various aquaculture species. Furthermore, numerous studies have highlighted the potential of chicken manure for aquaculture uses. For example, Knud-Hansen et al. (1993) claimed that chicken manure added to Nile tilapia, *O. niloticus* farming pond, could promote microalgae growth and act as a feed that could enhance the growth of farmed fish. Meanwhile, Mataka and Kang'ombe (2007) claimed that maize bran, in combination with chicken manure as a dietary supplement for *Tilapia rendalli* farming exhibited promising results. Despite that, fermented chicken manure was recently reported as bacteriologically safe compared to non-fermented chicken manure in Nile tilapia, *O. niloticus* farming (Elsaidy et al., 2015). Despite the potential to enhance fish production, a study highlighted the risk of farmed fish exposure to heavy metals (Nnaji et al., 2011) and coliform bacteria from chicken manure. Thus, the application of chicken manure in aquaculture requires proper disinfection to address the safety issues concerning aquaculture products for human consumption.

Pig manure

The swine by-product can be processed and utilised as a FM or soybean meal replacement as a protein source. Feeding trials were conducted using fermented pig manure and fresh pig manure in silver carp (*Hypothalmichthys molitrix*), bighead carp (*Aristichthys nobilis*), crucian carp (*Carassius auratus*) and common carp (*Cyprinus carpio*). The findings indicated that fresh pig manure promoted the growth of all the tested fish by more than 144% compared to fermented pig manure; thus, fresh pig manure can be used directly in fish farming. Meanwhile, Zoccarato et al. (1995) proposed that fresh pig manure can be directly applied as a fertiliser in carp fish *Cyprinus carpio* and *Ctenopharyngodon idella* farming in Northern Italy. In the study, high mortality was observed in the treatment using total pig manure, whereas a 100% survival rate was recorded when partial pig manure was combined with a commercial pellet. Therefore, Zoccarato et al. (1995) suggested that pig manure in moderation is acceptable to maintain good water quality and fish health. Conversely, Bwala and Omoregie (2009) found that a high dosage of pig manure in tilapia farming increased production and maintained optimal water quality in the fish pond. Moreover, pig manure was useful as a fertiliser by enriching phytoplankton and zooplankton in carp ponds (Dhawan and Kaur, 2002). A recent study by Tongmee et al. (2020) revealed that fermented pig manure could replace FM as a protein source up to 15% in Nile tilapia (*Oreochromis niloticus*) feed formulation without compromising their growth performance. Based on the literature, fresh pig manure can be applied directly into fish ponds as fertiliser to bloom phytoplankton and zooplankton as natural live feed for the aquaculture species.

Advantages of incorporating agricultural waste in aquafeed

Repurposing agricultural by-products as aquafeed is economical and environmentally favourable due to the improvement in waste management, reduced exploitation of natural resources, and enhanced general well-being of farmed fish. Infectious diseases have also become a main concern in the aquaculture industry. Additionally, more farms have intensified the culture systems to ensure a consistent and sufficient supply for consumers. Resultantly, aquaculture species stress levels will rise and impair their immune system, hence increasing their susceptibility to disease infection (Dawood et al., 2021; Hoseinifar et al., 2020; Kari et al., 2022 b, 2021, 2020; Van Doan et al., 2021). Synthetic antibiotics do more harm than good for the environment and consumers. Therefore, it is essential to opt for organic or environmental-safe supplements. Studies have shown that including agricultural waste-derived probiotics in supplements improves the immune system in farmed fish. Various research has evaluated the potential of primary agricultural wastes (Abdel-Latif et al., 2022; Dawood et al., 2021; Kari et al., 2022 a, 2020, 2022 c; Mat et al., 2022), and identified several agricultural wastes valuable for the aquaculture industry. Inexpensive and abundant agricultural wastes provide opportunities for aquaculture industry players to explore the properties and nutritional values of these wastes and sustain the agriculture industry.

In 2030, aquaculture production is expected to be approximately 109 million tonnes and to exceed fisheries production by 2050 as the main global aquatic protein producer (FAO, 2020). As the aquaculture industry is gearing toward tremendous expansion, more resources are vital in supporting the aquaculture industry development, such as new raw material for fish feed formulation, fertiliser to promote the growth of microalgae and other live feed and new antimicrobial or immunostimulatory agents to maintain the health of aquaculture species. Animal-based agricultural waste, such as blood meal, could compensate for the incomplete essential amino acids from plant-based ingredients. Despite the indispensable amino acid profile of blood meal compared to FM, an optimum balance can be achieved with other ingredients. Likewise, poultry waste is a protein form that can be readily digested by the fish and contains no cellulose.

Challenges of using agricultural waste in aquafeed and aquaculture practices

A classic challenge in using plant-based agricultural waste is the presence of anti-nutritional factors (ANFs) and high cellulose content. At a low level, ANFs is beneficial to the fish but not at higher concentrations. According to Soetan and Oyewole (2009) and Kari et al. (2021), ANFs are compounds that can reduce the nutritional value of plant products consumed by humans and animals. The ANFs are crucial in determining the suitability of plants as an ingredient in feed formulation. Several plant ANFs identified are tannins, phytate, oxalate, saponins, lectins, alkaloids, protease inhibitors, and cyanogenic glycosides (Gemede and Ratta, 2014).

The increasing utilisation of agricultural residues has prompted researchers to find ways to remove or reduce ANFs in plant proteins. Various methods have been established to extract ANFs from plant protein without reducing the nutritional values, namely soaking, germination, boiling, autoclaving, fermentation, and genetic manipulation (Thakur and Kumar, 2017). The fermentation process is one of the most popular and well-practised methods in the aquaculture industry. Today, fermentative nutrition in aquatic animals is still not well understood (Esakkiraj et al., 2009), but *in vitro* processing of plant ingredients via fermentation is recommended to decrease the ANFs and increase nutrient availability (Ramachandran and Ray, 2007). Nevertheless, fermentation is a new biological technique used on plant-based ingredients, such as soybean meal, to increase nutrient bioavailability through microbial enzymatic activities (Khan and Ghosh, 2013). Furthermore, the ANFs at low levels have a positive impact on animal health. For example, phytate, lectins, tannins, amylase inhibitors and saponins can reduce the blood glucose and insulin level in the body (Gemede and Ratta, 2014). Notably, pesticide residues in plant-based agricultural waste constitute a significant concern among fish farmers. Studies have shown that pesticides used for crops, such as paddy, can be detected in rice bran, leading to environmental and fish safety issues (Pareja et al., 2012). Likewise, synthetic antibiotics in animal waste, such as poultry waste (Gong et al., 2021), may affect the fish culture. The full impacts of pesticides and synthetic antibiotics on agricultural waste have not been explored in aquaculture; thus, more research is needed to evaluate the potential risk of synthetic residues from agricultural waste in fish.

Economic value and new product development from agricultural waste: waste to wealth

Advanced techniques and innovation have been developed to convert agricultural waste into valuable and sustainable resources (Duque-Acevedo et al., 2020). Basically, the waste management system consists of production, collection, storage, treatment, transfer and utilisation (Banga and Kumar, 2019). These fundamentals in the waste management system will lead to a more sustainable economy in the long term. Moreover, converting agricultural waste into wealth allows stakeholders to explore opportunities in a green environment, thus, improving fiscal activity and quality of life (Banga and Kumar, 2019). Researchers need to understand the market, consumer needs and competitors when establishing innovations involving agricultural waste for aquaculture usage. Consequently, the research products will be of superior value and cater to the needs of consumers (Schilling and Hill, 1998). Ultimately, new product development involving agriculture waste requires an in-depth analysis by researchers, which can be summarised into eight major steps (see Figure 3).

Figure 3. New Product Development process (Reid et al., 2016)

The concept of utilising agriculture waste in aquaculture begins with idea generation. Typically, researchers will generate hundreds of ideas based on the research (Nik Ahmad Ariff et al., 2013), including visualising, communicating, transferring (Ariff et al., 2012) and morphing the conceptual ideas (Jamaludin et al., 2015), before proceeding with prototyping and production to identify high potential ideas. Subsequently, researchers will conduct idea screening, concept development and testing, marketing strategy development, business analysis, product development, test marketing, and commercialisation.

Feed cost makes up 30–70% of the overall farm operational costs, influencing profitability in aquaculture investments (Daniel, 2018; Muzinic et al., 2006). Therefore, it is crucial to identify alternative protein sources as a FM replacement, which is gradually decreasing in production. A high-quality feed ingredient should yield the best growth and health performances in fish and have economic efficiency; thus, evaluating these criteria before introducing the feed to local farmers and feed producers is important. For example, Ngugi et al. (2016) reported that rice bran, in combination with *C. nilotica,* resulted in superior growth performance and suitable FM replacement without compromising economic benefits in Nile tilapia farming. Nevertheless, the same study observed that the fish growth performance was lower in fish fed solely with rice bran. In addition, Kishawy et al. (2021) revealed that rice protein sources exhibited no adverse effects on growth parameters besides offering high economic efficiencies and net returns. Furthermore, FM-based feed recorded the highest total feed cost per fish compared to other treatments. In conclusion, agriculture waste is a promising and potentially sustainable alternative in producing quality feed, which aligns with the waste to wealth concept.

Conclusion and recommendations

Years of research have revealed the potential of agricultural wastes for aquaculture applications. Agricultural by-products are highly nutritious and beneficial for aquaculturists, particularly in cost reduction. Furthermore, improper management of these wastes may lead to environmental pollution and harm public health. Therefore, converting these wastes into valuable resources is a good management strategy that can benefit communities, reduce environmental pollution and produce affordable aquaculture products. Despite that, several limitations have been identified in incorporating agricultural by-products in aquaculture activities, and studies regarding the potential risk and economic value of utilising agricultural waste in aquafeed remain lacking. Thus, it is recommended for future studies to conduct the necessary assessments and improvements before agricultural waste can become a mainstay in the aquaculture industry.

Author Contributions

Writing – original draft, review and editing: **Z.A.K, L.S.W, N.K.A.H, H.V.D**; Writing – review and editing: **S.A.M.S, N.D.R, K.M, N.N.A.Z, W.W**; Writing – review and editing on new product development section: **N.S.N.A.A, S.Z.A, M.B.M**; Writing – review and editing, conceptualization: **M.A.K, M.K.Z, K.W.G, M.I.K, A.T**.

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Conflicts of Interest

The authors declare no conflict of interest.

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