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REVIEW ARTICLE

Thought of Alternate Aquafeed: Conundrum in Aquaculture Sustainability?

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Abstract The exponential growth of human population and their ever-increasing demands have challenged the aquaculture sector with respect to its growth, sustainability and environmental well-being. Due to the rapid intensification, aquaculture's share of global fishmeal and fish oil consumption has more than doubled over the past decade with limited availability and high prices. Hence, the key concern of aquaculture in recent times is to reduce the environmental footprint while feeding the farmed fish with nutritionally balanced, economic and environmentally sustainable feed. But the changes in feed systems are dependent on several potential drivers, including environmental, political, economic, cultural, technological and demographic ones. The use of compound feeds formulated with a great variety of ingredients was a major step in the development of the worldwide aquaculture industry in the last century. However, the main challenges are the availability and cost of alternate feed resources, their competitiveness with other sectors, demand-supply consort with the environmental quality, social acceptability and economic growth. This review is an attempt to assess the present scenario of conventional aquafeed with an understanding of the gaining importance of alternate aquafeed along with their trade-offs addressing the principal issues of sustainability for future policy making.

Keywords Aquaculture · Aquafeed · Sustainability · Policy making

Introduction

A large proportion of the population in the developing countries suffers from chronic malnutrition despite continued efforts to provide a more stable, sustainable, and nutritionally balanced food supply. Aquaculture being the fastest animal producing sector, can promise to achieve Sustainable Development Goals (SDGs) by offering a sustainable food system to maintain global food security while securing economic benefits. However, unprecedented population growth and increased demands have challenged the growth of the aquaculture sector, along with increased requirements related to sustainability and environmental well-being (Thilsted et al. 2016; Sampantamit et al. 2020). In 2012, aquaculture provided almost 50% of all fish for human consumption and has been predicted to provide 62% by 2030 (FAO 2014, 2018). In this context, understanding on the nutritional requirements and production of fish feed became decisive factor for maintaining the sustainability of aquaculture along with its rapid intensification. To improve the sustainability and profitability of current aquaculture practices, a step towards the use of "nutritionally-complete formulated diets" with a great variety of ingredients has become a major challenge in the development of the worldwide aquaculture industry in the last century. But in the developing countries, aquatic animal nutrition and feeding has some definite issues to achieve sustainability i.e. (1) availability and cost of feed resources to develop alternate aquafeeds, (2) increasing competition of raw materials as resources with other sectors, and (3) demand-supply forestalling of local and global market in consort with the maintenance of environmental quality, social acceptability and economic growth of aquaculture systems (Hasan 2001; Caruso 2015). Against this background, the novelty of this review is to assess the

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present scenario of conventional aquafeed while understanding the gaining importance of alternate aquafeed along with their trade-offs by addressing the aforesaid issues (environmental, ecological and social) for future policy making to achieve SDGs.

The Conventional Dilemma

Fish meal (FM) and Fish oil (FO), originating from wild pelagic fish (forage fish), have been used in aquafeeds as the conventional main ingredients. But this practice is now under questioning for its nutritional quality and, more importantly, its dependence on wild fish stocks. With the rapid rise in aquaculture production since the 1970s, an increasing proportion of fishmeal and fish oil has become key source of both energy and essential fatty acids. Both FM and FO are high in protein, essential amino acids, minerals and are major dietary sources of n-3 long chain poly unsaturated fatty acids (PUFA), docosahexaenoic acid (22:6n-3) and eicosapentaenoic acid (20:5n-3). Total protein in fishmeal can be between 60 and 72% crude protein by weight. FM and FO have been reported to offer major benefits to animal health, including improved immunity against disease, higher digestibility, higher survival and growth, and reduced incidences of deformities. These qualities made FM and FO attractive for widespread use as nutritional ingredients in aquafeed (NRC 1998; Cho and Kim 2011). On the contrary, some FM and FO are made from wild fish containing high levels of heavy metals, dioxins and PCBs, are considered unsuitable for processing. Although, it is technically possible to decontaminate fish oil, but this increases the price (Le Gouvello and Simard 2017). Therefore, if suitable alternatives are not found, intensification of aquaculture and increasing demand may lead to fierce competition for the available supplies, overexploitation of the resources, and the inevitable escalation of cost of the feed. In this context, the stakeholders have been witnessing a steady rise in fishmeal price over the past few decades. The average annual price of fish meal was the lowest in 1994 and 1999 at 403 and 433 US$/tonne, respectively. Since 1999 the price had continued to rise reaching 1230 US$/tonne in 2009, then surged steeply to 1687 US$/tonne in 2010 reaching a peak of 1747 US$/ tonne in 2013. In the past decade (2006–2015) the fish meal price increased at an average annual growth rate of 8.94%.

A similar trend has been recorded in fish oil price. The lowest price levels of 325 and 262 US$/tonne were observed in 1994 and 2000, respectively. The price kept increasing at a slower pace until 2002, but gained momentum thereafter. After 2010, there was a sudden spike in fish oil price reaching a peak of 1923 US$/tonne in 2014. It is also interesting to note that the annual average fish meal prices were higher than fish oil until 2010, when fish oil became more expensive than fish meal (Salin et al. 2018). However, to offset high prices with increase in feed demand, the amount of FM and FO used in compound feeds for aquaculture has shown a clear downward trend, with their being more selectively used as strategic ingredients at lower concentrations and for specific stages of production, particularly hatchery, broodstock and finishing diets. At some point in the future, farmers culturing shrimp and carnivorous fish would run into a cost-price squeeze—the ‘fishmeal trap’—and that this might be the first of several ‘ingredient traps’ which might constrain certain forms of aquaculture in the future (Green and Authority 2016). It has been reported that out of the total fish catch, 27% is unutilized or lost between landing and consumption due to low value discards, storage problems and spoilage (FAO 2018). Indeed, the fish waste management has become a global problem from the environmental pollution perspective. To overcome this issue, the by-products like fish offal, silage and protein hydrolysate which are rich sources of proteins, minerals and vitamins, are also being used as a supplement in aquafeed (Esteban et al. 2007; Afreen and Ucak 2020). Fishmeal can also be produced from fish processing wastes (trimmings, offcuts and offal). Several attempts have been made to devise ‘fishmeal equivalent’ (FME) to take account not only of the use of commercially produced fishmeal in aquafeeds, but also the use of other marine ingredients, such as shrimp meal, squid meal, and trash fish (Wijkström and New 1989; FAO 2002). Now a days, 30–70% of the fish by-products, is processed into FM and FO, are primarily used for feed purposes (Taçon 1994; Schipp 2008; Green and Authority 2016).

In some countries, landed bycatch is being channelized into fishmeal production. The trash fishes are used as whole fish, used directly, or mixed as a slurry or mash. Frozen whole pelagic fishes are also used for fattening tuna and other large fish in cages (Huntington 2009). But in the last two decades the commercial and scientific interests have centred on lower trophic organisms with potential candidates like Antarctic krill (*Euphasia superba*) and calanoid copepods (*Calanus finmarchicus*) as an alternative to FO in fish feed (Olsen et al. 2004, 2006; Colombo-Hixson et al. 2011) due to having a uniquely high content of bioavailable phospholipid-bound n-3 LC-PUFA (Ulven and Holven 2015). To understand the contribution of these marine ingredients to global seafood supply and their impacts on all UN SDG’s economic allocation, the ‘Fish In: Fish Out (FIFO)’ ratio has become the principal metric. FIFO is being used successfully to ensure that the wild fish stocks are not negatively impacted by the aquaculture (Kok et al. 2020).

The limited availability and high prices of these raw materials could also be attributed to the following factors: the fluctuating state of fishery resources in the fishing zones, overexploitation of fish stocks, El Niño like event, the introduction of fishing quotas and increasing pressure to use fish oils and fishmeal in other markets such as health, food supplements and cosmetics (Fig. 1) (Le Gouvello and Simard 2017). A bio-economic model was developed to understand the connexion of ecological and the economic dynamics of the small pelagic fisheries and fishmeal/fish oil markets by Mullon et al. (2009). The model showed that the level of stock recovery after an El Niño event may proceed in two ways: if the stock recovers quickly, exploitation and markets reach a level like the levels preceding the El Niño event. If recovery is delayed, fishing pressure is likely to remain high during the recovering period, and both exploitation levels and markets must stabilize at a lower level than before the event. This is a mechanism that may endanger the global production system in the long run. With an estimated 5% increase in annual fuel prices, both the fishing and shipping costs are expected to increase considerably, leading to a drastic cut in the profit margin with ultimate decline in fishing capacity. While a high level of total allowable catch (TAC) results in overexploitation and price drop, a lower level of TAC leads to high prices and overcapacity (Pauly and Christensen 1995; Pinnegar and Engelhard 2008; Mullon et al. 2009). Collectively, these findings underscore the importance of the reduction in fishmeal dependency for achieving better sustainability with greater profitability of commercial fish farming enterprises.

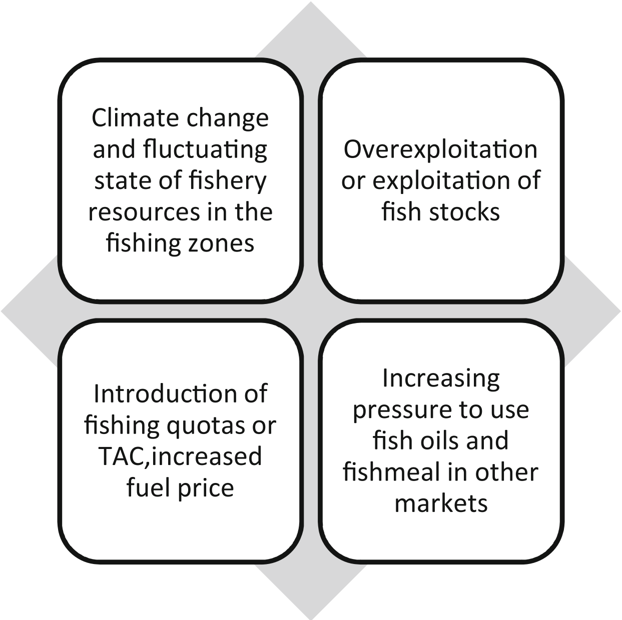


Fig. 1 Factors associated with the limited availability and high prices of FM and FO (Adapted from Pauly and Christensen 1995, Pinnegar and Engelhard 2008; Mullon et al. 2009; Le Gouvello and Simard 2017)

The Alternate Trade-Offs

Several options are available to supplement or replace the FM and FO as alternatives to meet the future requirements for proteins. For instance, carbohydrate or lipid-rich diets have been extensively used in aquaculture feed manufacturing to reduce nitrogen emissions and to minimize protein use. Other advantages are getting cheap dietary energy through the ontogeny, a relatively constant chemical composition and easy availability in the world market (Gatlin et al. 2007a, b; Hardy 2010). Several investigators have emphasized on the protein-sparing effect of carbohydrate in different species like *Oreochromis niloticus* × *O. aureus* (Shiau and Peng 1993), *Labeo rohita* (Jafri 1995), *Puntius gonionotus* (Mohanta et al. 2007), *Clarias gariepinus* (Orire and Sadiku 2014), *Scopthalmus maximus* (Zeng et al. 2015) and *Heteropneustes fossilis* (Rahman et al. 2017). Lipid supplementation in fish diet, on the other hand, have yielded increased profit in fish culture (Steffens 1996; Ovie et al. 2005; Li et al. 2012; Welengane et al. 2019). Despite these advantages, the suitability, sustainability, and acceptability of the alternate protein sources in aquafeed to the consumers, producers, purchasers, and policymakers are not clear. To be a viable alternative, a candidate ingredient must possess certain characteristics, including nutritional suitability, ready availability, and ease of handling, shipping, storage, and use in feed production. Additionally, the feeds must be selected based on fish health and performance, consumer acceptance, minimal pollution and ecosystem stress, and human health benefits (Naylor et al. 2009; Burr et al. 2012).In this section of the review, a holistic assessment has been done to address these issues to portray a clear picture of different alternatives available as aquafeed till date.

Plant Based Alternate Feed

The use of plant protein in fish feed industry has been endeavoured since last few decades for various commercial culture fish species, mainly due to the higher contents of proteins, amino acids and fatty acids compared to the animal sources (Mondal and Payra 2015). These plant products contain lesser amounts of phosphate and nitrogen than that of animal proteins. Hence, they have little contribution to environmental degradation. Plant source feedstuffs suitable for fish feed formulation include pods, seeds, leaves, fruits of certain plants, grains, oilcakes like linseed, safflower, sunflower, soybean, roots, cereals and cereal by-products, broken rice, rice polish, tubers of sweet potato, wheat bran, maize, cassava, sorghum, etc. Grasses, vegetables, aquatic weeds, plant's leaves, stems, seeds and seed extracts are also used in fish feed industry (Mondal et al. 2012; Dorothy et al. 2018). About 50 species of aquatic macrophytes have been reported as direct or indirect food to 40 species of herbivorous fish in tropical and subtropical countries. These macrophytes can be used as fish food components to replace costly commercial feed owing to their excellent nutrients profile: moisture ranges between 84.1 and 95.9%, dry matter 4.1–15.9%, crude protein 8.7–26.8%, crude fat 2.2–5.1%, carbohydrate 9.3–35.6%, ash 8.0–25.3%, and crude fibre 15.0–28.1%, with caloric content of 2.47–4.2 kcal g^{-1}. The partial replacement of the fishmeal with these plant-based products showed satisfactory growth in food intake, feed conversion ratio and relative growth rate of different fish species of various age groups. With tremendous potentiality as alternate fish feed, utilization of these terrestrial and aquatic plants in preparation of fish feed offers an opportunity of livelihood to the rural people (Mandal et al. 2010; Dorothy et al. 2018).

Among the vegetable materials of terrestrial origin, soybean (*Glycine max*) meal is considered as the most valued product, due to its high protein value, essential amino acid content and easy availability. The soybean is grown as a commercial crop in over 35 countries as the major oilseed (Smith and Huyser 1987). The crude protein content of soybean seed is around 44–49%. The amino acid contains considerable quantity of lysine (6.2 g/16gN), with methionine and cystine content of 2.9 g/16gN. The fat content varies between 15.5 and 24.7%, crude ash 4.5 to 6.4%, neutral detergent fibre (NDF) 10 to14.9%, acid detergent fiber (ADF) 9 to 11.1%, and carbohydrates content between 31.7 and 31.85% on a dry matter basis (Ensminger et al. 1990; NRC 1998). Despite these positive points, however, soybean meal has been criticized for multiple reasons that include: high land-use requirement; significant environmental deterioration including deforestation, soil erosion and eutrophication; extensive use of pesticides and consequent loss of biodiversity; and a huge carbon footprint. Moreover, soybean meal has low palatability and lower content of sulphur-containing amino acids methionine and cysteine. More importantly, soybean meal can inflame the digestive tract of the fishes, because of the presence of anti-nutritional factors (Arru et al. 2019; Parolini et al. 2020).

Vegetable oils can also replace fish oils, provided that essential fatty acids (EFA) are added to the formulated feeds for some fish species, or at certain stages. Among the vegetable oils, rapeseed, soybean, palm, groundnut and sunflower oil are the most readily available ingredients. To replace FO in aquafeeds a wide variety of oils containing the health-promoting and highly sought n-3 LC-PUFAs (namely EPA and DHA) can be derived from wild-caught marine organisms, such as krill, amphipods, copepods, and mesopelagic species (Olsen et al. 2014). However, their commercial exploitation is not favoured for the same reasons that advocate reduced reliance on traditional FO. Instead, oils containing higher amounts of n-3 LCPUFAs have been developed from several non-marine microalgae and single-cell organisms (Ganuza et al. 2008; Hemaiswarya et al. 2011; Eryalçin et al. 2015; Sprague et al. 2015; Sarker et al. 2016), and genetically modified oilseed crops (Kitessa et al. 2014; Betancor et al. 2015, 2016).These oils offer exciting opportunities for the sustainable expansion of the aquaculture sector. Later studies revealed that genetically engineered oilseed crops, Camelina (*Camelina sativa*) and Canola (*Brassica napus* L.) offer a natural way of increasing the supply of n-3 LC-PUFA with significant amount of EPA and DHA for providing nutrition to different life history stages of farmed fishes (Sprague et al. 2017). However, a partial knowledge gap on species-specific and age- specific individual fatty acid requirements should be addressed.

Studies have shown that nonessential amino acids (NEAAs) and conditionally essential amino acids (CEAAs) have significant role in the fish health, growth, and overall performance (Wu 2014). Research in amino acid nutrition technologies, including EAAs, NEAAs, and CEAAs, is expected to play a critical role in shaping the viability and sustainability of aquafeed formulation and manufacturing (Li et al. 2009). In several countries, the use of terrestrial plant-based products in aquaculture has been deplored by public opinion. Studies also showed that soy and palm oil is the most widely traded vegetable oil globally, with demand projected to increase substantially in the future along with the demand from aquaculture. As the oil palm's range is limited to the humid tropics, much of this expansion has come at the expense of species-rich and carbon-rich tropical forests. Oil palm was responsible for an average of 270,000 ha of forest conversion annually from 2000 to 2011 in major palm oil exporting countries (Henders et al. 2015). The conversion to date, and future expansion, impacts local forest ecosystems, threatens biodiversity, and increases greenhouse gas emissions. However, for some countries, these crops represent an opportunity for socio-economic development. Labels of responsible production can contribute to improving acceptability to consumers. But there is a lack of real demand from end-users and the producers involved in these initiatives are still few, although their numbers have increased significantly in recent years. In addition, nearly half of the certified palm oil on the market cannot find a buyer (Vijay et al. 2016).

In general, agricultural commodities have good consumer acceptability. This is particularly the case of pulses such as alfalfa, peas and fava beans. When the plants from which the raw materials obtained are GMOs, however, there are potential causes of rejection in certain countries regarding the toxicity and (or) allergenicity of the novel protein, potential unintended effects, and risk of horizontal gene transfer to other species. Admittedly, several studies have been performed to understand the effect of herbicide-tolerant GM plants and insect resistant (Bt) plants in fish feeds of salmon and channel catfish, rainbow trout, and zebra fish. Still, more research is needed to evaluate the physiological effect of GMO plants on fish (Sissener et al. 2011). As such, certified non-GM pulses are more expensive in many countries due to their reduced availability and/or logistic constraints. Thus to incorporate more alternative plant-based raw materials in aquaculture feed formulas, the non-GMO constraints must be confronted or lifted (Van Huis and Itterbeeck 2013, Le Gouvello and Simard 2017,Gasco et al. 2018).

Corn (maize) gluten, a by-product of the corn starch manufacturing industry, is another promising plant protein source. It has a 45–50% crude protein content but is deficient in some amino acids, especially arginine and lysine. However, it can be used along with other protein sources in aquafeeds. Preliminary studies have shown that corn gluten can partially replace (10–15%) fishmeal in Indian white shrimp feed (Ahmed Ali and Dayal 2004). Corn gluten has also been evaluated in the diets of Indian carps (Kaur and Saxena 2004). Groundnut cake is extensively used in fish and shrimp feeds due to its ready availability. Although its use in high quality shrimp feeds is limited, groundnut cake is utilized in considerable quantities in farm-made feeds and by small-scale feed producers. Lupin (*Lupinus albus*) is a non-starch legume; its seeds have a good potential for aquaculture diets due to its higher protein content (30–40 g/100 g) than most of the other grain legumes and low price (Rajeev and Bavitha 2015).

Rice protein concentrate (75% crude protein, lipid content 11% ether extract), rapeseed and sunflower meal, protein-rich crops or fodder/forage crops, many by-products (from biofuel, beer production, rubber production, starch, substitution of hydrocarbons etc.) with potentially high nutritional value, competitive prices are being used as alternate feed raw material due to easy availability. Studies have been carried out to understand the efficiency of plant based proteins on feeding, digestibility, nutrition and growth performance in fishes. The reduction in the feeding and growth in response to higher levels of dietary plant proteins has been reported in several aquatic animals due to the nature of plant proteins having less apparent digestibility coefficient (Gatlin et al. 2007a, b), intestinal damage (Yu et al. 2015), deficiency of one or more essential amino acids (EAAs) (Bautista-Teruel et al. 2003), less palatability (Torstensen et al. 2008) and presence of anti-nutritional factors (ANFs) like alkaloids, oligosaccharides, phytate, saponin and protease inhibitors (Welker et al. 2016). ANFs play a limiting effect on fish growth. Moreover, they may cause pathomorphological changes in the intestinal epithelium of fish (Krogdahl et al. 2003; Glencross et al. 2004; Ostaszewska et al. 2005a, b; Caruso 2015). In addition, increase in muscle protein degradation has been reported (Snyder et al. 2012). In contrast, a large number of researchers reported positive effects or no adverse effect on digestibility and nutrition upon partial replacement of fish meal with plant based materials in different fishes including grass carp (Köprücü and Sertel 2012), hybrid sturgeon (Sicuro et al. 2012), turbot (Bonaldo et al. 2015), common carp (Suprayudi et al. 2015) and Senegalese Sole (Valente et al. 2016). Gatlin et al. (2007a, b) proposed the criteria for plant based alternate feed (PBAF) components: availability at a reasonable price, transportable and fit into the feed production plant; containing low fibre, starch (especially non-soluble polysaccharides) and anti-nutritional compounds; high protein content with a favourable amino acid composition with good palatability and digestibility by the target species (Table 1). A range of measures have been proposed to overcome these constrain including: genetic manipulation of the plants and the fish species to remove or deal with antinutritional compounds; the use of pre- and probiotic materials alongside the PBAF and the use of processing treatments to eliminate anti-nutritional factors and improve palatability before incorporation in the feeds.

Table 1 Criteria for Plant Based Alternate Feed (PBAF) components as alternate aquafeed

Local availability and reasonable price
Transportable and fit into the feed production plant
Contain low fibre, starch (especially non-soluble polysaccharides) and antinutritional compounds (alkaloids, oligosaccharides, phytate, saponin and protease inhibitors)
High protein content with a favourable amino acid composition
Good palatability and digestibility by the target species
Low carbon footprint
Acceptability by the consumer

Land-Based Animal By-Products

Land based animal products can be harvested from livestock farming and from ruminants, pigs, poultry, and insects. Animal fat and Processed Animal Proteins (PAPs) can be obtained from different slaughter by products from healthy animals: meat, fats, blood, feathers and other legitimate parts of the carcass. The defatted meal, being richer in CP than soybean meal and fish meal, has become a protein-rich resource in fish diets (Le Gouvello and Simard 2017). An extensive scientific literature is available on their high nutritive value and digestibility of rendered animal proteins for aquaculture species (Luzier et al. 1995; Bureau et al. 1999; Nengas et al. 1999; Bureau et al. 2000; Kureshy et al. 2000; Wang et al. 2006). Most studies have focused on the use of these ingredients individually, reporting incorporation levels of 5–25% (El-Haroun et al. 2009). The results from a large majority of these studies suggest that rendered products are cost-effective sources of several key nutrients (lysine, sulphur amino acids, histidine, arginine, and phosphorus), fatty acids, and several other nutrients. In addition, most animal by-products are highly palatable to most fish species. Rendered animal fats, because of their low costs and wide availability, could be interesting alternative for part of the fish oil in fish feeds (Bureau et al. 2002). Studies showed that 50% replacement of fishmeal by poultry by-product meal did not adversely affect hematological parameters of *Sparus aurata* juveniles indicating good fish health. But high dietary levels of PBM reduced the liver gene expression of GH/IGF axis and of cathepsin D suppressing fish growth and modulating the protein turnover (Karapanagiotidis et al. 2019). The growth performance parameters were best at treatment fed with 10% blood meal inclusion level, no mortality recorded and with the best feasible cost. The poorest was found at treatment fed with 15% blood meal inclusion level which also recorded the highest mortality rate in African Catfish *Clarias gariepinus* juveniles (Njieassam 2016). Approximately 35% of fish meal protein could be replaced by both fermented and unfermented blood meal for juvenile Silver *Pompano Trachinotus* blochii without compromising growth performance and feed efficiency, potentially leading to significant cost (Hamed et al. 2017). However, individual rendered animal protein meals, such as blood meal or hydrolysed feather meal often have deficiencies or excesses in essential amino acids that may affect the overall productivity of cultured fish (Fasakin et al. 2005).

Several studies have shown positive effects when two or three alternate protein sources are used in various combinations in fish feed formulation to reduce the effects of nutrient imbalance, excessive levels of anti-nutritional factors or lower palatability in various fish species (Fowler 1991; Steffens 1994; Nengas et al. 1999; Bureau et al. 2000; Millamena 2002; Guo et al. 2007). For the aquaculture feed manufacturer, the PAPs can be a good choice due to its availability from close geographical areas, and their good quality/price ratio. The development of new technologies, in the perspective of the circular economy, can help to reduce waste production throughout the PAPs production chain. Due to innovative bioprocesses, discards can provide precious nutrients, such as protein, fatty acids, peptides, chitin, collagen, carotenoids, and minerals, useful in aquaculture nutrition. But these compounds either in liquid or solid state have short shelf life, although this problem could be solved by implementing a stable and continuous cold chain on the entire processing line (Shabani et al. 2018; Gasco et al. 2020). Some nutritionists underestimate the digestibility and the nutritional value of animal proteins. This misperception dates back many years to when poor processing techniques and equipment were used to render animal by-products. Since that time, new processes, improved equipment, and greater understanding of the effects of time, temperature and processing methods on amino acid availability have resulted in significant improvements in the digestibility of animal proteins. Three primary food safety issues dominate discussions about the safety of feeding animal proteins to animals. These are *Salmonella* contamination (bacterial pathogens), BSE and dioxins. Each of these issues present legitimate concerns and all are known to threaten animal and human health. Additionally, the use of by-products of porcine origin is clearly banned in some countries for religious reasons (Schreuder et al. 1998; Hamilton 2004).

Insect Meal

Insect meal is also a highly environmentally friendly source of nutrients, in accordance with Goal 14 of the Sustainable Development Goals. Insects contain high levels of protein and their production has a small ecological footprint (Chaalala et al. 2018). Producing insect meal requires limited land and water. Insects can sustainably close nutrient cycles while providing animal proteins and useful by-products, creating employment, increasing local productivity and connecting smallholder farmers to the agribusiness value chain (Chia et al. 2019). Although highly acclaimed introduction of insect meal into fish feed is currently not economically viable for small- to medium-sized aquaculture businesses and as only the consumers who perceived more benefits are more willing to accept the use of insects to feed fish (Domingues et al. 2020). At present, insect flour cannot be an alternative for the troubleshooting of economic sustainability problems of aquaculture enterprises. This is because the current insect meal and food production are not sufficient to ensure a constant supply. A recent report estimates that the animal insect

Table 2 Strength of Insect meal as alternate aquafeed

High levels of protein and lipid
Local availability and small ecological footprint
High biological value and FCR
High demand, low cost and consumer's willingness to accept
Employment generation with increasing local productivity while connecting smallholder farmers to the agribusiness value chain

production market is worth half a billion dollars, with a growth forecast of over $1 billion by 2022, meaning that insect feed could account for up to 3% of the entire production of the feed market within the next 4 years (Arcluster 2017). Integrating insect farming into other agricultural products is also an interesting path to explore. The crude protein (CP) content of insects ranges from 42 to 63%, which is equivalent to soybean meal and fish meal. Insects are part of the natural diet of freshwater and marine fish, especially in the juvenile stage. Insects often accumulate fat, especially during their immature stages (Manzano-Agugliaro et al. 2012; Gasco et al. 2018). The lipid content of non-defatted insects varies from 8.5 to 36%. However, variability in lipid concentration is high even within the same species, influenced by the stage of development and by the diet (Barroso et al. 2014). The strength of the insect meal as alternate fish feed has been summarized in the Table 2.

Currently the insect rearing companies have focused on insects as feed for animals like reptiles, snakes and other insect eating pets. The price for insects is still high when compared to traditional fishmeal or soybean meal. Automating the rearing process appears to be the most important step to reduce the costs of labour (Vrij 2013). In this context, utilization of the maggot meal in aquaculture industry will not only reduce the cost of waste disposal but will serve as a means of generating additional income, especially in integrated fish systems as maggots are usually considered to not have any economic value (Ajani et al. 2004). When fishmeal is replaced by insects the total protein level is important, but even more important is the amino acid composition. Adesulu and Mustapha (2000) reported that cystine, histidine, phenyalanine, tryptophan and tyrosine in magmeal are higher than that in fish meal and soybean meal. Magmeal is also rich in phosphorous, trace elements and B complex vitamins (Teotia and Miller 1973). The crude protein and lipid content in maggot meal ranges between 40 and 58%, with 5–8% crude fibre and 0.56–1.4% ash (Ajayi, 1998) without any anti-nutritional or toxic factors. Therefore, magmeal can be a viable alternative protein source and can replace fishmeal by 25–100% in different aquaculture species (Spinelli et al. 1979; Fashina-Bombata and Balogun 1997; Ajani et al. 2004). With 52–72% of crude protein and highly enriched with different essential amino acids such as valine, lysine, methionine and phenylalanine, silkworm pupae can replace fishmeal up to 50% (Begum et al. 1994). Indeed, it is considered an important feedstuff (either single, compound diets or processed) in Asian aquaculture with good growth and feed conversion rate (Hodar et al. 2020). Feeds based on black soldier fly larvae can open additional marketing opportunities for farmers as some customers are opposed to the use of fishmeal in aquaculture feeds (Tiu 2012). Especially in the developing countries where fishmeal is imported with high cost, the insect meal can be viable and sustainable option due to its low cost, local availability, biological value and feed conversion ratio (FCR; Hodar et al. 2020) and promoting alternative livelihood. Moreover, the uses of locusts and grasshoppers as the alternate fish feed can aid in biological control, and the harvesting may help to reduce the application of chemical pesticides and thereby environmental pollution (Khusro et al. 2012).

Earthworm Meal

The use of earthworms as an alternative protein source for fish is an opportunity for providing environmental services via cleaner technologies as this can be efficiently grown on substrates that are waste or by-products owing a very low or null economic value (Parolini et al. 2020). Earthworms dry matter (16–20% of fresh matter) contains from 55 to 70% of proteins, 6–11% fat, 5–21% carbohydrate, and a range of vitamins (including niacin and vitamin B12) and 2–3% minerals with a higher content of essential amino acids (lysine and methionine) compared to fishmeal (Mohanta et al. 2016). Previous literature reported successful replacement of fishmeal by earthworm meals in different fish species reporting higher weight gain, FCR and digestibility in *Clarias batrachus* (Ghosh 2004); *Labeo rohita* (Mohanta et al. 2016); *Parachanna obscura* (Vodounnou et al. 2016) with varying percentage. Djissou et al. (2016) reported that a mixture of earthworm and maggot meals in catfish fingerling can reduce 50% cost by substituting the fish meal. Although it is still expensive compared to conventional protein sources. The Life Cycle Assessment (LCA) approach to quantify the environmental impact related to earthworm meal production showed that the emissions of methane and N-compounds was the main environmental hotspots while the impact related to fresh earthworm processing to meal has a lower impact except than for lyophilization process (Conti et al. 2019; Tedesco et al. 2019).Thus there is a strong need to identify the best substrate(s) to grow earthworms efficiently while assessing the environmental impact. Researches must be carried out to understand the potential adverse effects due to the inclusion of Earthworm meal in fish feed, bioaccumulation of organic and inorganic contaminants and pathogens during vermicomposting. Further we must quantify the optimal level of Earthworm meal substitution in fish feed while considering the consumer perception and the willingness-to-pay as a local and less environmental impacting alternate protein source (Parolini et al. 2020).

Single Cell Protein

SCP products can be prepared from different microbial sources, including microalgae, fungi and bacteria. SCP also acts as an immunostimulant and probiotic, substantially improve growth, health, disease resistance and immune system of cultured organisms (Ige 2013). Previous literatures showed that macro- and micro-algae have significant nutritional qualities as fish feed supplement as algae can directly produce HUFA such as arachidonic acid (AA, 20:4n-6) (*Porphyridium*), eicosapentaenoic acid (EPA, 20:5n-3) (*Nannochloropsis*, *Phaeodac-tylum*, *Nitzschia*, *Isochrysis*, *Diacronema*) and docosahexaenoic acid (DHA, 22:6n-3) (*Cryp-thecodinium*, *Schizochytrium*). Cultivated microalgae has fundamental importance in the hatchery production of many farmed fin-fish, shellfish and other commercially important aquaculture species as "green water" or "pseudo-green water" rearing technique. However, a study performed by Gamboa-Delgado et al. (2019) on shrimp, using different ratios of Spirulina (*Arthrospira platensis*), *Nannochloropsis ocultata*, and fishmeal, showed that *Nannochloropsis ocultata* was a poor replacement of fishmeal. Although, macroalgae are less widely used in aquaculture, they are the important source of nutrition for certain farmed invertebrates and shell fish. The importance of different algal strains in aquaculture hatcheries, their cultivation tech-niques, methods of delivery and modes of opera-tion (Muller-Feuga et al. 2003a,b, 2004; Zmora and Richmond 2004; Tredici et al. 2009; Conceição et al. 2010; Guedes and Malcata 2012) can be found in previous literatures. SCPs are capable of synthesizing carotenoids de novo, which improves the flesh color of various fishes like red porgy, *Pagrus pagrus,* penaeid shrimp, *Litopenaeus vannamei, ornamental fishes* (Chatzifotis et al. 2011, Parisenti et al. 2011), and increase the market value (Zat'ková et al. 2011; Sergejevová and Masojídek 2011; Ritala et al. 2017). The production of organically certified salmon exclusively requires sup-plementation of dietary astaxanthin (derived from *Haematococcus plu-vialis)* to achieve the pink colour of the fillet (Shields and Lupatsch 2012). However, comparatively few studies have been carried out to comprehend the magnitude of microalgal lipids farmed fish feed (Atalah et al. 2007; Ganuza et al. 2008; Tredici et al. 2009). The technical and nutritional potential of algae is strengthened by advantages on a social level. Many algal species are marine and generally their acceptability as aquaculture feed is a good choice due to their naturalness. Although their quality of the environment in which it was grown or been harvested should be considered.

Salmon and shrimp have been the major focus of recent yeast feeding trials (Jones et al. 2020). Different yeast meals (*Saccharomyces cerevisiae, Candida utilis, Kluyveromyces marxianus and Yarrowia lipolytica)* at different proportions in the diet of Salmon and shrimp were assessed to understand the growth performance and nutrient utilization as an alternative of conventional meals (Øverland et al. 2013; Gamboa-Delgado et al. 2016; Álvarez-Sánchez et al. 2018; Hansen et al. 2019; Guo et al. 2019). Several studies were performed to comprehend the effect of growth and feed efficiency of partial inclusion of bacterial protein meal (BPM), biofloc meal in the diet of salmon (Aas et al. 2006), trout (Hardy et al. 2018), shrimp (Tlusty and Thorsen 2017; Chumpol et al. 2018; Hamidoghli et al. 2019). A microbial biomass mixture of bacteria and microalgae has been extensively tested on black tiger shrimp (*Penaeus monodon*) to overcome the growth disadvantages when fishmeal and fish oil are removed from the prawns' diet, and another study depicted the improved growth rates when Novacq is included at 10% of the diet (Glencross et al. 2014; Arnold et al. 2016). But the key concerns to use the SCPs are the RNA content, toxins produced by microbes (production hosts or contaminants) and harmful substances derived from the feedstock such as heavy metals. Though techniques have been developed in recent times and are in industrial use to decrease the RNA content to acceptable level. As some fungi produce mycotoxins and this makes them undesirable sources of SCP, the challenge of toxins can be overcome by carefully selecting the strain, the process conditions, and the product formulation (Anupama and Ravindra, 2000). Single-cell protein production recycles wastes from agriculture and industries because these substances can be utilized by microbes as nutrient sources. Feed-derived wastes and ammonia released from cultured organisms can also be recycled through SCP (Bharti et al. 2014).

The use of microbial feed additives, the probiotics (live microbial feed supplements which beneficially affect the host animal by improving microbial balance) in particular, in commercial aquaculture feeds has become an emerging issue in the later part of the twentieth century. Probiotic microbes have revolutionized the economic growth by enhancing survivability, disease resistance, digestive efficiency, and growth performance (Balcázar et al. 2006; Denev et al. 2009; Nayak 2010; Ganguly and Prasad 2012; Ray et al. 2012; Dehaghani et al. 2015). But the use of live probiotics in the exposed aquaculture farms may cause ecosystem based complications as there is a potential procurement of virulence genes and antibiotic confrontation by parallel gene transfer through the gram-negative probiont and antibiotic-resistant microorganisms (Newaj-Fyzul et al. 2014). In addition, most probiotic products sold in the developing countries lack information on the concentrations of different species, strains and hence, became a serious issue while considering the of quality of the products (Nimrat and Vuthiphandchai 2011).

Biofloc Meal

With the advent of environmentally sustainable aquaculture "Biofloc Technology (BFT)" (Emerenciano et al. 2013) has been proven to increase the aquaculture feasibility by reducing feed conversion ratio and a decrease of feed costs by producing in situ microbial protein with carotenoids, amino sugars and vitamins (Ju et al. 2008). The dried floc meal may be used as beneficial ingredients in fish. It contains many nutrients and components such as protein, which are ranged between 24 and 50% and lipids ranged between 0.5 and 3.5% (Hodar et al. 2020). This mixture represents as an unconventional ingredient to replace fishmeal and other protein sources in fish or shrimp diets (Dantas et al. 2016). It was also reported that the extracellular floc organisms may contain enzymes that help to improve digestion process inside fish gut (Moreno-Arias et al. 2017), growth rate (Wasielesky et al. 2006), decrease FCR and associated costs in feed (Burford et al. 2003; Panjaitan 2004). Bioflocs also offers a lot of MAMPs (microbial associated molecular patterns), which are recognized as immunostimulants, resulting in higher resistance to diseases (Ekasari et al. 2014, 2015). Thus, biofloc systems having high productivity and profitability from the same area of land with fewer input utilizing fewer resources and at the same time has lower impact on the environment (Asche et al. 2008; FAO 2017). But the system in its infancy stage (Bossier and Ekasari 2017).

The Way Forward

To offer a more environment friendly fish production process, profit maximization should be pursued using resources efficiently and minimizing environmental impact. For this, the aquaculture enterprises should bear the burden of new eco-friendly production techniques and feed, which are often more expensive than those used at present (Arru et al. 2019). It is argued that "there's no alternative to sustainable development" and the scientists have advocated unification of the concept of environmental sustainability with economic efficiency (Nidumolu et al. 2009). Recently a study was conducted to comprehend the incremental fishmeal substitution by plant ingredients in shrimp feed to understand the environmental sustainability by identifying the resource implication on marine and terrestrial resources such as fish, land, freshwater, nitrogen, and phosphorus (Malcorps et al. 2019). The results showed that complete substitution of 20–30% fishmeal could lead to increasing demand for freshwater (up to 63%), land (up to 81%) and phosphorus (up to 83%) causing additional pressures on essential agricultural resources with associated socioeconomic and environmental effects as a trade-off to put pressures on finite marine resources. Changes in feed systems are dependent on several potential drivers, including environmental, political, economic, cultural, technological and demographic characteristics (De Brauw et al. 2019). To pursue the Sustainable Development Goals (SDGs), the economic dimension of sustainability must go in concord with environmental and the social one. A wide range of raw materials must be promoted to encourage dynamism of economically accessible aquafeed while maintaining product quality. Profit maximization can be achieved by reducing environmental impact initiatives through cheap and proper management practices i.e. by producing by-products (fish meal, fish oil, fish silage and organic fertilizers) as alternates.

The knowledge about these issues is still fragmented in term of geographic area (Parolini et al. 2020).Scientific researches will be useful to understand the biological effects of these feeds to encourage best processing process (Kennelly and Broadhurst, 2002; Arvanitoyannis and Kassaveti, 2008; Gálvez and Berge 2013). The formulation of diets needs consideration of the relative cost and availability of different ingredients as well as their nutritional value. A lower percentage of fish meal substitution, by introduction of rendered protein sources and adjustments of the plant protein sources, lead to better economical conversion rates, with consequent better economic profit index, by minimizing the final cost of the diet.

However, the prices of raw materials and feed ingredients differ internationally on the basis of each country's importation tariffs, energy costs, seasonal factors, economic status of the country. Moreover, it depends on the global markets (Serwata 2007). The major restraint of rendered animal products in fish feeds is consumer acceptance. Although these ingredients have proven to be effective substitutes in temperate, tropical and marine fish species, their role must be addressed in the light of new information and public acceptance in large scale as most of the alternatives decouple the economic activity from the consumption of finite resources, and designing waste out of the system focusing on sustainability. More researches are needed to understand sensory evaluation of fish subjected to dietary formulations containing terrestrial animal derived proteins compared to standard marine protein-based feeds of the final product (Nogueira et al. 2012). In recent times, the insect business is a fast-growing sector, and several companies or start-ups have been underway but the major constraint limiting their growth is legislative barriers (Lähteenmäki-Uutela et al. 2018). Although, the apparent willingness to use insects for feeding fish should be promoted by encouraging mass insect production. Assessment of the consumer's acceptability of fish reared on insects is necessary to ensure market for insect-fed fish (Ssepuuya et al. 2019). Moreover, future researchers could investigate not only using insects as a protein source, but also as "additives" to modulate microbiota and animal health (Gasco et al. 2018; Arru et al. 2019).

Increasing the use of crop-based ingredients in commercial aquaculture feed is not the solution as the current world agriculture system is based on the long, complex and interdependent, globalised food supply chain which has led to a loss in diversity of the crops grown. In recent times, a limited number of crop species dominate, and monoculture is increasingly practiced which also affect the production of plant- based aquaculture feed. But the knowledge is still lacking with regard to the indirect negative environmental health externalities caused by industrial crop production methods and their impact on human health through changing nutritional content of aquaculture products. With the higher proportions of crop-based ingredients,aquaculture production will be further decoupled from conventional supplies, thus creating a feedback loop and will increase the demand higher than projections based on historical trends (Hall 2015).

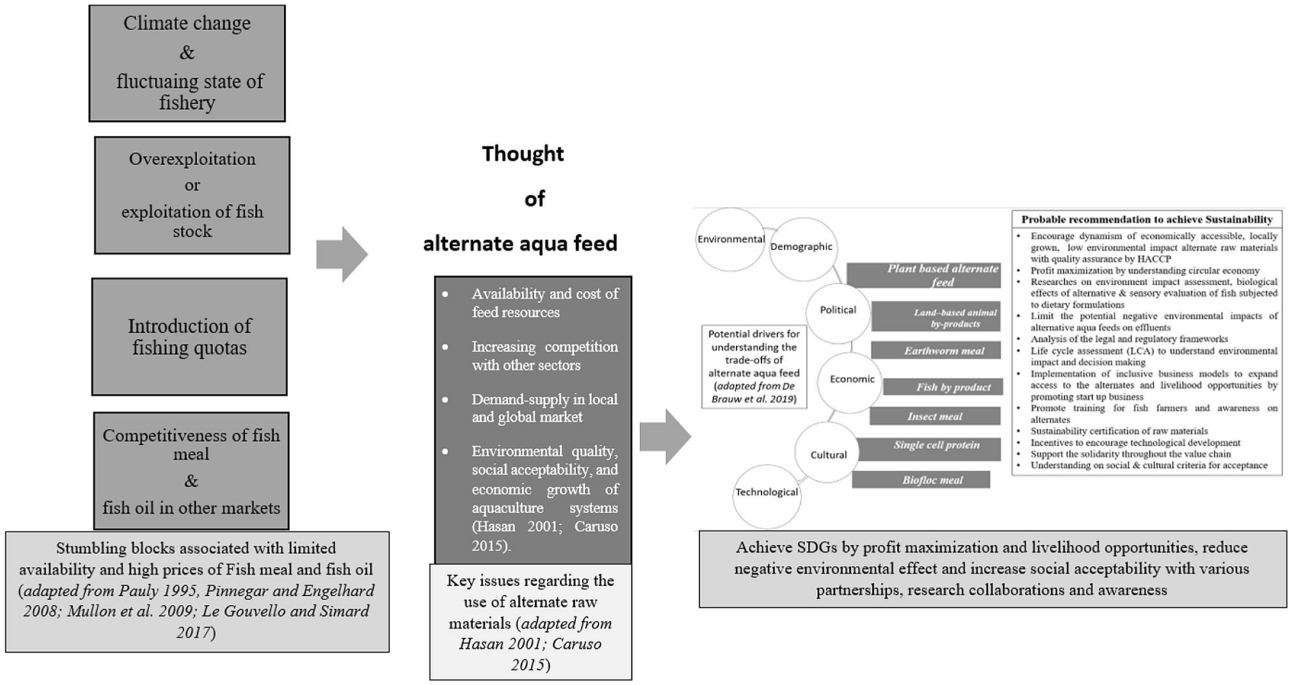
The economic disarray in aquaculture sector caused by infections directed the inclusion of antibiotics in the diets of aquaculture species. But the forbidden use of human antibiotics as growth promoters in the diet of animals since the year 2006 by the European Union, along with the use probiotics in recent years, there is a parallel evolution of the alternatives to growth promoters. In the process, the Prebiotics (non-digestible sugars that induce the growth or activity of beneficial microorganisms) and Synbiotics (synergism of probiotics and prebiotics form) have emerged as inducers of health-improving microorganisms by triggering the activities of their metabolism. Their combinations also achieved good health and growth performance in aquaculture species (Kim et al. 2011; Bozkurt et al. 2014; Das et al. 2017). The feed production industry is currently subjected to threats of an overabundance of the commercially accessible of these feed additives. The regulation of their commercial usage can be sustainably managed by bridging the gap between the "science-based" understandings and its application, establishment of laborious, efficient assessment skills and enforcing the laws (Amenyogbe et al. 2020).

To promote sustainable utilization of alternate aquafeed, there is a strong need to select ingredients which can be supplied sustainably, grow locally and with low environmental impact. Additionally, it should support small-scale farming systems, Moreover, farm-made aquafeeds should offer better feed management systems and better quality ingredients maintaining quality and safety. Climate change is one of the debateable issues in recent years. Aquaculture, being a regulated environment, may be better placed to adapt to climate change. Where open ponds or marine environments are used, the effects of the environmental impact must be abridged by high nutrient density and digestibility, and wider issues such as energy use in aquaculture (Tacon et al. 2011; Hall 2015).

The institutions and authorities should take pivotal roles to promote training for fish farmers to understand the double edge of alternate raw materials and how to produce nutritionally balanced high-quality fish feed by using the local ingredients. An entrepreneur's increasing competence could motivate the production scale and risk making new investments in this type of farm using alternate feed. There is the need for quality control policy by the government to regulate fish feed manufacturing (Gabriel et al. 2007). A consistent Sustainability certification of raw materials and ingredients should be encouraged to promote sustainability in aquaculture. Establishment of rendering companies may also support industry programmes to certify compliance for preventing and controlling BSE using third-party auditors. HACCP programmes require an evaluation of the entire rendering process, identification of potential hazards. Cultural criteria can also influence the positions and opinions of other stakeholders or communities for using these alternate raw materials (Hamilton 2004).

An analysis of the legal and regulatory frameworks including the establishment of minimum feed performance criteria (e.g. feed conversion ratio, nutrient digestibility), placing restrictions on nutrient composition in formulations (e.g. nitrogen and phosphorus levels) and feed use, and restricting environmentally unsustainable feeding practices should be taken into account to promote better management practices. In many production systems, feed management affects the quality of farm effluent streams limiting the quality and/or quantity of effluent and treatment regulations prior to discharge. Therefore, the authorities should take the initiative to ban the use of specific potentially high-risk feed items such as fresh/trash fish and invertebrates. In addition, efforts should be made to minimize the feed performance criteria (specific levels of allowable dust/fines, feed efficiency or nutrient digestibility, for example) to assess the environmental carrying capacity of the receiving aquatic ecosystem. Moreover, treatment of the farm effluents prior to discharge and limiting or fixing the total quantity of feed and the concentration of specific dissolved/suspended inorganic/organic materials and/or nutrients contained within the effluent discharged from the farm over a fixed time period should be carried out by implementing the environmental monitoring program and good management practices for farm operations including feed manufacturing. However, to promote this framework for environmental protection, the authorities must be practical and acquainted with the implementation and compliance costs, and the ability of the specific country or farming sector to absorb these costs (Tacon and Forster 2003; Shipton and Hecht 2013). The inclination of consumers and retailers to purchase farmed fish that is fed on recycled animal protein and oil or genetically modified plant is debatable for long. Incentives will be needed to encourage technological development of nonforage fish inputs in feeds. In recent years the volatility of commodity prices has created disincentives to long-term ingredient purchasing and systematic changes in feed formulations (Naylor et al. 2009).Thus, it is imperative to work in parallel to develop medium and long-term strategies to build a more resilient, sustainable, and equitable food system (Fry et al. 2016).

The environmental impacts connected to an entire production system can be conveniently evaluated using life cycle assessment (LCA) methodology (ISO 2006a; b), although some studies of LCA of aquafeed have ignored these methodological variations (Papatryphon et al. 2004). Use of different LCA approaches has yielded different impact results, where attribution LCA has underestimated the environmental impacts of aquafeed manufacturing. System expansion yields the highest estimate of emission embodied in aquafeeds across all impact categories, indicating that consequential LCA is the most appropriate approach if the purpose of LCA is to support decision making in weighing policy options. The limitations associated with consequential LCA methodology need to be investigated in future studies, especially in identifying the marginal products in aquafeed manufacturing (Samuel-Fitwi et al. 2012). Implementation of sustainable business solutions such as inclusive business models, is likely to expand access to the alternate raw materials, services, and livelihood opportunities for low-income communities in commercially viable ways (Bonell and Veglio 2011).Thus, the smallholder farmers will benefit from new markets while generating meaningful profits and increasing economic resilience in low-income communities. Developing the institutional drivers will be vital for successfully implementing the use of alternate feed via inclusive business models. To support the solidarity throughout the value chain, from upstream to downstream, from manufacturers



Stumbling blocks associated with limited availability and high prices of Fish meal and fish oil (*adapted from Pauly 1995, Pinnegar and Engelhard 2008; Mullon et al. 2009; Le Gouvello and Simard 2017*)

- Availability and cost of feed resources
- Increasing competition with other sectors
- Demand-supply in local and global market
- Environmental quality, social acceptability, and economic growth of aquaculture systems (Hasan 2001; Caruso 2015).

Key issues regarding the use of alternate raw materials (*adapted from Hasan 2001; Caruso 2015*)

Potential drivers for understanding the trade-offs of alternate aqua feed (*adapted from De Brauw et al. 2019*)

Probable recommendation to achieve Sustainability

- Encourage dynamism of economically accessible, locally grown, low environmental impact alternate raw materials with quality assurance by HACCP
- Profit maximization by understanding circular economy
- Researches on environment impact assessment, biological effects of alternative & sensory evaluation of fish subjected to dietary formulations
- Limit the potential negative environmental impacts of alternative aqua feeds on effluents
- Analysis of the legal and regulatory frameworks
- Life cycle assessment (LCA) to understand environmental impact and decision making
- Implementation of inclusive business models to expand access to the alternates and livelihood opportunities by promoting start up business
- Promote training for fish farmers and awareness on alternates
- Sustainability certification of raw materials
- Incentives to encourage technological development
- Support the solidarity throughout the value chain
- Understanding on social & cultural criteria for acceptance

Achieve SDGs by profit maximization and livelihood opportunities, reduce negative environmental effect and increase social acceptability with various partnerships, research collaborations and awareness

Fig. 2 Delineating the stumbling blocks associated with the use of conventional aquafeed, key issues and factors driven trade-offs to use alternate aquafeed, with probable recommendations for achieving sustainability of raw materials, aquaculture feed manufacturers, aquaculture producers and to consumers there is a need to strengthen the communication, to make it more relevant and adaptable (Le Gouvello and Simard 2017; Chia et al. 2019). More research is needed to quantify the nutritional and functional interactions among alternative raw material ingredients in a more integrative, holistic, and multifactorial way to achieve sustainability (Glencross et al. 2007; Turchini et al. 2019). Aquaculture is intricately associated with different aspects of the SDGs. Considering the aforesaid issues during policy making, the promotion of alternate ingredients as aquafeed can help us to achieve SDGs by profit maximization and livelihood opportunities. Moreover, it is expected to reduce negative environmental effects. Consequently, it will increase social acceptability with various partnerships, research collaborations and awareness.

Summary

A comprehensive overview has been illustrated (Fig. 2) encompassing the status quo concerning the use of conventional aquafeed, to understand the key issues and factors driven trade-offs while using alternate aquafeed, with probable recommendations for achieving sustainability.

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