Harnessing the Power of Microbial Consortia for Sustainable Fish Waste Treatment

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Introduction

The global population is expected to reach 9.8 billion in 2050 and 11.2 billion in 2100 (UN report 2017), significantly increasing the demand for food. Further, the increasing economic growth and growing awareness of balanced nutrition shift the nutrition demand of people towards higher consumption of animal-based products and diverse food items. Among different food production sectors, the fisheries sector is critically important in providing food safety and employment for the growing global population. Currently, fish provides > 4.5 billion people with a minimum of 15% of their average per capita animal protein intake (FAO 2016). Fisheries and aquaculture have been the world's fastest-growing food industries for the last 40 years and this trend is predicted to continue (Bene et al. 2015). The global fisheries and aquaculture production has reached 223.2 million tonnes in 2022 with a 4.4% increase from 2020 (FAO 2024). As a result, there has been a sharp increase in fish waste worldwide. It is estimated that ~10% of the global fish catch (>90 million tonnes) is currently discarded, and fish processing wastes including heads, bones, scales, viscera, gills, and skin account for up to 70% of the whole fish weight (Boronat et al. 2023).

Impacts of fish waste

Fish waste is a menacing issue and a major source of environmental pollution, necessitating creative solutions to implement sustainable waste management methods. As fish wastes are rich in nutrients (58% and 19% of dry matter is protein and fat, respectively), unless efficiently managed, they will be dumped in the environment causing pollution from organic matter, nutrients, and chemicals used in fish processing (Selvi et al., 2014). Improper fish waste disposal can disrupt aquatic ecosystems. The accumulated waste overloads the water with nitrogen, phosphorus, and ammonia, causing a pH shift and increased water turbidity. Fish waste produces harmful hydrogen sulphide, ammonia, and greenhouse gases like carbon dioxide and methane exacerbating climate change if not managed sustainably. Release of toxic gases, oxygen depletion, and pH change produce harmful algal blooms and negative impacts on aquatic and marine life. It leads to increased scavenger gatherings at discharge locations and noxious conditions brought on by bacteria, odours, and waste decomposition (U.S. Environmental Protection Agency Report, 2010). Improper management of fish waste will detrimentally affect human health, by contaminating water supplies, increasing the prevalence and spread of infectious diseases, and degrading local water supplies and groundwater.

Valuables resources from fish waste

Addressing the burden of fish waste management requires a comprehensive approach that includes improving waste treatment technologies, promoting sustainable fishing and processing practices, enhancing regulatory frameworks, and encouraging the utilization of fish waste in value-added products. Fish waste management techniques and utilization/ further processing of fish waste in each place are dependent on the local conditions and the structure of the industry. The most common value-added products from the fish waste include organic fertilizers, animal feeds, silage, and feed supplements (fish oil, fishmeal, fish silage, calcium supplements), biogas and bioenergy, protein hydrolysates (can be used as a milk replacer and food flavouring agents), antioxidants and bioactive peptides that have applications in nutraceuticals, pharmaceuticals, and functional foods, natural pigments, chitin (applications in the production of biodegradable plastics, water treatment, and as a feed additive), industrial enzymes (proteases, alkaline phosphatase, hyaluronidase, acetyl glucosaminidase and chitinase), fortified foods, cosmetics, pharmaceutical products such as collagen, chitosan, gelatin, fish bone extracts, amino acids, and polyunsaturated fatty acids. The synthesis of surgical sutures from fish gut, the use of fish scales as natural adsorbents and in ornamental applications, the production of short-chain organic fatty acids, use as substrates for microbial culture media, the creation of attractants for commercially significant flies, and the production of fish glue from fish skin and heads are additional value-added options for fish waste.

Benefits of fish waste as an organic fertilizer

The six macronutrients for plants are nitrogen, phosphorous, potassium, calcium, magnesium, and sulphur. Even though fertile soils can deliver a significant share of these nutrients, most soils require a regular input of fertilizers containing these six macronutrients and preferably thirteen micronutrients for successful growth. Fish waste usually contains significant amounts of nitrogen, phosphorous, calcium, and sulphur, even though they are less well-balanced concerning potassium and magnesium. The average nitrogen content in fish waste is ~12–13% of dry matter. The composition of nutrients in fish waste varies between different fish species, size and with the inclusion/exclusion of tissues like head, bones, and viscera. The average nitrogen content in the powder from trimmings was ~14% compared to 5–7% of DM from the powder from frames and gills. The fish bones contain ~60 to 70% minerals, mainly in the form of calcium and phosphorus as hydroxyapatite. The average phosphorus and calcium content in the fish bones was 170 and 221 g per kg dry matter, respectively. Fish scales are very rich in nitrogen (5 to 11% of dry matter), phosphorus and calcium. Generally, the average values of N-P-K for inland captured and marine captured fish were 120:11:13 and 130:16:11, respectively. However, the potassium content was low in fish waste, ranging from 0.003 to 1.7 g per kg dry matter. The major difference between shellfish waste and finfish waste is that shellfish waste contains a large amount of chitin due to shell residues. Altogether, different studies showed that fish waste possesses substantial amounts of nitrogen and minerals, and thus can play an important role in meeting the nutritional requirements of crop plants (Ahuja et al. 2020).

Composting fish waste for organic fertilizer

Composting is an old practice and simple technique for controlling environmental pollution. Composting is the biological alteration of waste materials, under controlled conditions, into a hygienic, humus-rich, relatively stable bioproduct that conditions soils and nourishes plants (Mathur, 1991). It is an aerobic biological decomposition of organic matter by microorganisms. It is essentially similar to the natural decomposition process except that it is accelerated by mixing organic waste with other ingredients to optimize microbial growth. The resulting product termed ‘compost’ enhances the physical properties of soil like total porosity, available water content,

saturated hydraulic conductivity, and organic matter. Fish remains are a preferred substrate for fertilizer due to their high nutritional value. Composting initiatives using fish waste have been done worldwide as a viable technique for converting fish waste into useful agricultural products (López-Mosquera et al. 2011). Composting can effectively reduce the volume of fish waste and demolish disease-causing organisms and larvae of flies from waste. The composting of fish waste for producing organic fertilizers has received attention in recent years to increase the economic and ecological sustainability of the fish industry, however, the technique is not well-popularised in India (Jayvardhan and Arvind 2020). As fish waste is rich in protein, the compost merely based on fish waste tends to have a low C/N ratio. Hence, "bulking agents" are required for an adequate composting process. Adding bulking agents also facilitates aeration through the pile and provides carbon sources for microorganisms. The rapid release of ammonia from protein degradation of fish wastes and calcium from fish bones tends to shift the pH of the compost mixture towards the alkaline range, where adding bulking agents with acidic characteristics contributes to a decrease in pH. Further, the water-absorbing character of the bulk agent helps to control the moisture components of the fish wastes. Different bulking agents include sawdust, rice hulls, coconut pith, wood chips, bark, crop residues, leaves, crushed grass, wheat bran, agricultural wastes, peat, seaweeds, poultry litter, and straw.

Fish composting has been evaluated from very simple to complex composting techniques such as in-vessel composting bays, compost-pits and bin systems including three-bin systems, wooden crates, reactors, ceramic pots, and passively aerated windrow method. The maturation of the fish waste compost with peat moss in a passively aerated windrow method took 8 to 10 weeks.

Operative constraints in the composting process

1. ***Aeration***: Many aerobic microbes involved in the bioconversion process require oxygen for their growth and other metabolic processes. Anaerobic degradation will be

adopted in the absence of sufficient oxygen, which will eventually cause the emission of malodorous gases. Aeration also aids in regulating the moisture content and temperature by dissipating the heat produced during the composting reactions. Conversely, over-aeration dries out the mixture and produces low temperatures that are inappropriate for the composting process. If the composting time is four months, it is advised to turn the pile once every two weeks for the first two months and once every fifteen days for the final two months.

2. ***Carbon to nitrogen ratio (C: N)***: The available carbon to nitrogen ratio needs to be maintained at the right levels to support an active microbial population during the composting process. Higher ratios will cause the composting process to take longer, while lower ratios will cause nitrogenous compound losses. The optimal C: N ratio of the total substrate in compost should be between 20 to 30 (Busato et al., 2018)
3. ***Moisture level***: Water provides a medium for the bioconversion activities in the compost mixture and is necessary for the survival of microbial populations. Low moisture content will slow down the decomposition of compost, but flooding the compost site will prevent the gas exchange that is necessary for aerobic processes. The optimum moisture range for composting operations is 40-60%.
4. ***Temperature***: In the composting process, temperature affects the microbial population and bioconversion rates. Temperatures in the range of 32°C to 60°C indicate the rapid progression of the decomposition process in the compost. Reduced temperatures indicate the slow progression of the composting process. However, high temperatures >65°C result in a reduction in the activity of the majority of microorganisms. The compost pile must maintain the composting materials at a temperature between 131 °F (55°C) and 170 °F (76°C) for a minimum of three days to destroy

weed seeds, pathogenic microorganisms, eggs of parasites and fruit flies.

5. ***pH***: A good composting performance is indicated by the pH of the final compost as 6-8.5. Release of carbon dioxide and ammonia during the degradation of protein-rich wastes such as fish waste will impart acidic and alkaline characteristics respectively, which tend to neutralize the pH value of compost without the need for external modification
6. ***Site for composting***: The composting should be done at least 100 m from surface waterways and far enough away from residential areas to protect from odours (EPA, 1996). The compost area needs to be set up on an impermeable base like concrete that is graded so that runoff and leachate drain into a pit or collection tank. The tank should be big enough to keep things from overflowing. A shade is also required to avoid the dryness of the pit/ compost pile.
7. ***Minimization of odour***: The primary cause of odour development in fish waste composting is the generation of anaerobic conditions within the compost piles. Odorless carbon dioxide is the primary gas produced by composting under aerobic conditions. On the other hand, volatile fatty acids, ammonia, methane, and hydrogen sulfide are produced under anaerobiosis. By adding fish wastes to the composting process on the same day as their generation, odours can be minimized. To effectively control odours, aerobic conditions must be maintained through frequent compost pile turnover or ventilation systems. Preserving compost at the proper carbon-to-nitrogen ratio will also reduce odour even further.
8. ***Minimization of dust formation***: Dust can be effectively managed by mild water spraying. While the high-water content of compost makes dust generation unlikely, its existence can be interpreted as a warning of insufficient moisture in the compost.

Assembly of compost windrows/piles: A source of carbon (bulking material) and a source of nitrogen (fish waste) are the only two basic requirements for composting fish waste. Three or two parts carbons to one part nitrogen is a basic formula. Accordingly, fish waste is mixed with the selected bulking agent during the composting process. The size of the compost pile might vary depending on the available space; nevertheless, a minimum of 10 cubic feet, or 3 feet × 3 × 3 feet, is advised for productive degradation. For minor volumes of waste, an ordinary compost bin can be used for composting. The compost bins vary from small plastic backyard bins holding about 9 cubic feet of material to larger mechanically rotated bins holding several cubic yards of materials. In commercial or municipal composting facilities, materials are usually placed on the ground in long narrow piles, called windrows. Composting is carried out on enormous concrete pads in certain plants. Windrow turners or mechanical aeration may be applied for turning the piles. A 200 mm thick base layer of bulking material is laid at the bottom to build the compost windrow's base. On top of this substrate, layers of bulking materials and fish waste are put alternately at 1: 2 to 3 proportions. The width and height of these windrows may reach up to 3 m. The windrow may be extended lengthwise when it reaches its tallest point. The compost pile can be covered with a thick layer (~150 mm) of mature compost or bulking material to keep away flies, birds, and odours. Approximately 2 tonnes of fish waste will create a compost windrow measuring 3 m wide by 10 m long containing four layers of waste materials. Seasonal effects can influence the proportional quantities of the required fish wastes and bulking agents. In rainy periods, the extra bulking agents should be added to increase absorbency while slightly less bulking agent may be necessary during dry periods. Depending on the structure of the pile and the type of materials used, unturned compost will sufficiently mature in about one year. Turning the compost windrow three to four times will help maintain an even temperature throughout and will hasten the decomposition process. To reduce the spread of odours downwind from the composting site, avoid turning windrows on windy days. The compost is sieved using a 20-mm mesh screen after it is deemed mature.

Role of microbes in the composting process

The biological phase of the composting process encompasses microbes and hydrolytic enzymes present in plant materials and animal tissues. The biological phase regulates the outcome of the whole composting process. Fish viscera contain several degrading enzymes, however, these enzymes can function at the start of the composting process because as the composting progresses, the enzymes will become damaged. As a result, microbes continue to be the primary component of the composting process. Since only 5–10% of the total microbial population represents the actual degraders during the natural composting process, it is advantageous to use different beneficial microorganisms in the composting process. As a result, traditional composting without the aid of an effective microbial consortium is exceedingly labour-intensive, and inefficient, and may produce a less valuable soil amendment. An easier mode to achieve beneficial microbes is through adding a small amount of immature compost from a different composting process. The increasing mandate for valuable composts has exaggerated the exploration of beneficial microorganisms for improved composting processes.

Microbes for turning fish waste into fertilizer

Creating an effective microbial consortium for fish waste composting involves selecting a diverse group of microorganisms that can work synergistically to break down various components of fish waste efficiently. An ideal consortium for enhancing fish waste composting should include:

1. Ammonia oxidizing bacteria
2. Nitrite oxidizing bacteria
3. Sulphur oxidizing bacteria

4. Proteolytic bacteria
5. Chitinolytic bacteria
6. Lipolytic bacteria
7. Phosphate solubilizing bacteria

Since fish waste includes large amounts of ammonia, which is harmful to plants, ammonia-oxidizing bacteria that convert ammonia to nitrite is an essential component in the fish waste-degrading consortium. Further oxidation of nitrite to nitrate, the form of nitrogen mainly assimilated by plants through nitrite-oxidizing bacteria is another important process. As ammonia oxidation is often the rate-limiting step during the composting process, adding ammonia and nitrite-oxidizing bacteria can improve the quality of the final compost. The action of sulphur oxidizing bacteria in compost results in the formation of sulphate, which can be used by plants, while the acidity produced by oxidation helps to solubilize plant nutrients and improves alkali soils. Similarly, the phosphate-solubilizing bacteria can increase plant growth by solubilizing the sparingly soluble inorganic and organic phosphates. The effective conversion of fish waste into a beneficial fertilizer also requires bacteria that can break down the organic components of fish waste, specifically the protein, lipid, chitin, and cellulose of bulking materials. Combining these microbes into a consortium ensures a comprehensive breakdown of fish waste, resulting in high-quality compost. Proper conditions such as moisture, temperature, and aeration should be maintained to support the activity of these microbes.

In this context, it is worth mentioning that ICAR-CMFRI has developed an indigenous microbial consortium that can degrade the fish and shellfish waste and a novel composting technology applying the consortium that can efficiently convert various marine fish waste into valuable organic fertilizer.

Salient details

- The raw materials included marine fish trash comprising both finfish and shellfish, a carbon source, and an indigenously developed consortium. The developed consortia had two components with part I containing thermotolerant microbes (to be applied at the initial stage of composting) and part II containing mesophilic microbes (to be applied after the thermophilic stage of composting).

- On the first day, all the raw materials are mixed in the proper ratio with the required volume of water, followed by building the compost pile and covering it with a garden mesh net to keep out the flies. The mixing is repeated on the fifth day with the required volume of water. The mesophilic microbial consortium (part II) is added on the eighth day of composting with proper mixing. Mixing is repeated on the 10th and 15th day to maintain aeration. At every turning time, the necessary amount of water is added to balance the moisture level.
- The compost became fully matured and stable by 20-25 days of composting as per the results of seed germination assay, temperature and pH dynamics, ammonia & nitrate concentrations, and C: N ratio.
- There was a 3-4 times reduction in the weight by 20-25 days of composting