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REVIEW

Appraising waste from fed aquaculture animals as a food source for sea cucumbers

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Abstract
Nutrient-rich solid waste and effluent water from aquaculture remain a major problem for aquaculture in terms of environmental impact. Integrated multitrophic aquaculture (IMTA), where lower trophic level species consume the waste of fed animals, has been proposed as an alternative for sustainable aquaculture. The use of deposit-feeding sea cucumbers as extractive species in IMTA has attracted research and commercial interest in recent times, due to their low trophic level, high commercial value as food for humans, and ability to ingest sediment containing organic matter, bacteria, protozoa, diatoms, and detritus. Still, the suitability of using faecal waste from fed aquaculture animals as a potential feed requires further studies to ensure not only palatability but also nutritional value, health, and immune responses of the cultured organism. This review discusses various performance indices, such as palatability, ingestion rate, assimilation rate, faecal production rate, feed conversion ratio, growth, and survival of sea cucumber species fed various faecal wastes from different aquaculture animal sources. It further discusses various IMTA applications of sea cucumbers with selected animals. The compatibility, viability and efficacy of sea cucumbers and some aquatic animals in IMTA are summarised.

Keywords Integrated multitrophic aquaculture · Sea cucumber · Sustainable aquaculture · Biodeposit

Introduction

Aquaculture waste is derived from uneaten feed lost to the environment and consumed feed which is unassimilated and lost as respiratory by-products and excreta (Quinn et al. 2016). Waste produced from feed is influenced by the composition of the feed, the method of feed production, the ratio of feed size to animal size, the amount of feed given to the animals at

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a time, and the method of feeding and feed storage (Boyd 2015; Miller & Semmens 2002; Sun et al. 2016). Feed produced for aquatic animals typically contains high amounts of dietary protein required to meet the animal's metabolic processes (Craig et al. 2017; Granada et al. 2016). Protein consists predominantly of nitrogen and phosphorus (Craig et al. 2017), and due to this, excretory waste and leftover feed contain high percentages of these elements. Waste can either be solid or dissolved waste. Solid waste is typically derived from unconsumed feed and faecal waste and could either be settleable solids that sink quickly or suspended solids. Dissolved waste is generated from food metabolism in aquatic animals and the decomposition of uneaten feed (Cripps & Bergheim 2000; Dauda et al. 2019). When these wastes become excessive in a culture system, it leads to poor water quality, negatively impacting the cultured animals (Bao et al. 2019; Devi et al. 2017).

Waste from aquaculture and effluent water remains a significant problem for aquaculture in terms of its environmental impact thereby affecting sustainability (Edwards 2015; Ni et al. 2018; Ottinger et al. 2016; Onomu & Okuthe 2024a). The waste is often flushed into the surrounding environment, negatively impacting water quality and resulting in eutrophication, algae blooms, turbidity, and increased chemical and biological oxygen demand (Onomu et al. 2024a). The process of waste degradation leads to increased oxygen consumption, carbon dioxide and ammonia production, and mineralisation of elements such as nitrogen and phosphorous, all of which are detrimental to the health of both vertebrates and invertebrates in the water body (Boyd & McNevin 2015; Bureau & Hua 2010).

One practice used to minimise the impact of aquaculture effluent is integrated multi-trophic aquaculture (IMTA). IMTA involves rearing two or more species of different trophic levels in the same culture medium (Chopin et al. 2004). The animals selected for IMTA are complementary to each other and are mutually beneficial (Langdon et al. 2004). In IMTA, the waste output, which in monoculture would have been flushed out from higher trophic level species, is used as an input (fertiliser, feed, energy) for the complementary animals at lower trophic levels. This results in greater overall productivity and reduced waste (Langdon et al. 2004; Neori et al. 2004). The concept of IMTA is therefore viewed as an approach to reduce excess nutrients produced using monoculture while producing an additional product (Chopin et al. 2004). However, before a species is considered for inclusion into IMTA, it is first necessary to investigate if the intended extractive species can utilise the waste of the fed species as feed.

The use of sea cucumbers as an extractive species due to their low trophic level and ability to process aquaculture-impacted sediments is gaining popularity (Onomu et al. 2023; Onomu et al. 2024a, b, c; Onomu et al. 2025a , ; Slater & Chen 2015; Zamora et al. 2016). However, a major limitation of sea cucumber farming is identifying food sources that can meet their nutritional needs and maximise growth (Onomu et al. 2024a, b, c). Aquatic animals require energy to maintain metabolic activity, growth, reproduction, and health. This energy is supplied by macronutrients (protein, carbohydrate, and lipid). These macronutrients are needed for growth, tissue repair, health, and reproduction (Lovell 1989). It is, therefore, paramount that diets meet the dietary requirements of the species to be cultured. There is a paucity of literature regarding the dietary requirements of sea cucumbers; literature is only available for *A. japonicus*, *S. japonicus*, and *H. scabra*.

Deposit-feeding sea cucumbers ingest sediment containing organic matter, bacteria, protozoa, diatoms, and detritus from either plants or animal sources (Liu 2010; Zamora et al. 2016; Zamora & Jeffs 2012). Sea cucumbers can ingest uneaten feeds and faeces of marine animals and even ingest their own faeces (Israel et al. 2019; Ramofafia et al. 1997). Faecal waste from animals is desirable as food for sea cucumbers, possibly due to the bacteria, diatoms, cyanophyceans, and foraminifera associated with it (Hamel et al. 2001). The nutrient available in fed aquaculture species waste depends on the nutrient levels in the animal feed, the assimilation rate, and the digestive efficiency of the animal. Therefore, leftover feed and the faeces of fed aquatic animals can serve as a suitable food source for sea cucumbers (Chen et al. 2015a; Domínguez-Godino & González-Wangüemert 2019; Jin et al. 2016; Mathieu-Resuge et al. 2020; Maxwell et al. 2009; Onomu et al. 2023; Slater et al. 2009; Yuan et al. 2006; Zamora et al. 2014).

While there is research supporting the use of aquaculture waste as a food source for sea cucumbers, there is currently no review on the subject. In this light, this review aims to examine the potential use of waste from aquatic animals used in fed aquaculture as a feed source for other animals, focusing on sea cucumbers. In the following, key parameters for assessing the suitability/value of solid wastes from fed aquaculture for IMTA use for deposit-feeding sea cucumbers are reviewed and discussed.

Performance of sea cucumbers fed aquaculture waste

This section reviews instances where faecal waste was fed to sea cucumbers and includes the waste of various fed and unfed aquaculture animals such as shrimp, fish, mussels and oysters (Bauer et al. 2019; Slater et al. 2009; Yu et al. 2014; Zhou et al. 2017a, b). Waste has been used both fresh and dried. The limitation of using fresh waste as feed is associated with challenges of preservation. The primary means by which waste can be preserved is through refrigeration which requires costly energy resources. To overcome this limitation, sea cucumbers can be integrated directly into places where faeces settle when the culture system is flushed. If direct integration is not feasible, an alternative is drying the waste; however, when wastes are dried, the nutrient content is reduced as drying denatures the nutritional components (Yuan et al. 2006). The methods used to assess the suitability of a feed source for sea cucumbers in this study are ingestion rate (IR), assimilation efficiency (AE), faecal production rate (FPR), growth, and feed conversion ratio (FCR) (Zamora and Jeffs 2011; Onomu et al. 2023).

Ingestion rate (IR)

As palatability is a significant factor that influences feed intake, ingestion rate can be used as a tool for feed quality assessment, in that it quantifies the palatability and acceptability of a particular feed (Eriegha & Ekokotu 2017). Low palatability and poor feed acceptability can lead to inadequate ingestion, resulting in poor growth (Eriegha & Ekokotu 2017). The IR depends on the animal's size, food source, digestion, nutritional physiology, and bioenergetics (Maxwell et al. 2009; Xu et al. 2015). The sea cucumber, *Stichopus monotuberculatus*, ingested shrimp *(Litopenaeus vannamei)* waste at a rate of 0.02 g g^{-1} d^{-1} (dry weight [dw]) (Chen et al. 2015a). Similarly, the sea cucumber *Neostichopus grammatus* ingested abalone (*Haliotis midae*) waste at a rate of 0.03 g g^{-1} d^{-1} (dw) (Onomu et al. 2023). Slater et al. (2009) used the faeces of the green-lipped mussel as feed for the sea cucumber *Australostichopus mollis*, in which waste was consumed at a rate of 0.31 g g^{-1} d^{-1} (dw). Rainbow trout waste, eel waste, and experimental formulated feed were used to feed (*A. japonicus*) (Jin et al. 2016). The ingestion rate of those fed eel waste was significantly higher at 0.27 g g^{-1} d^{-1} (dw), than those fed rainbow trout waste and formulated feed (Table 1). The IR of sea cucumbers fed on waste from fed aquaculture from the studies above ranges from 0.02 g g^{-1} d^{-1} to 0.31 g g^{-1} d^{-1}. Of the species of sea cucumber

Table 1 Nutrient composition of waste from fed aquatic animals used to feed sea cucumber and their effect on growth

Group of fed species	Source of waste given to sea cucumbers	Feed given to animals	Dry matter (%)	Crude protein (%)	Crude lipid (%)	Carbohydrate (%)	Ash (%)	Organic matter (%)	SGR (% d^{-1})	Source
Crustaceans	Wet shrimp waste (*L. vannamei*)	Commercial feed[1]	ND	23.19 ± 0.08	0.45 ± 0.01	1.51 ± 0.03	53.47 ± 0.11	46.53 ± 0.11	0.300	Chen et al. (2015b)
	Dried shrimp waste (*L. vannamei*)	ND[2]	95.80	5.50 (SD)	0.60	15.60	73.80	26.20*	−0.58 ± 0.21	Broom et al. (2021)
Molluscs	Cultured bivalves [including scallop (*Chlamys farreri*; *Argopecten irradians* and *Patinopecten yessoensis*) and oyster (*Crassostrea gigas*)]	Natural microalgae[2]	98.97 ± 0.02	1.40 ± 0.16	0.36 ± 0.05	6.22*	92.02 ± 0.02	7.98*	−0.66	Yuan et al. (2006)
	Green lipped mussel waste (*Perna canaliculus*)	ND[4]	ND	5.1 ± 0.06 (SD)	1.0 ± 0.15	19.6 ± 0.25	72.30 ± 0.56	15.10 ± 0.42	0.32	Slater et al. (2009)
	Abalone faeces (*Haliotis iris*)	50% *Undaria pinnatifida* and 50% *Macrocystis pyrifera* [3]	88.60	17.60	1.90	35.00	45.50	54.50*	ND	Maxwell et al. (2009)
	Abalone faeces (*H. iris*)	50% *Undaria pinnatifida*; 25% *Macocytis pyrifera* and 25% formulated diet[3]	89.10	14.30	1.70	21.30	63.00	37.00*	ND	Maxwell et al. (2009)
	Abalone faeces (*H. midae*)	Commercial feed, *Ulva rigida* and *Gracilaria gracilis*[5]	ND	16.25 ± 0.09	1.3	13.65	65.2*	34.80 ± 0.24	ND	Onomu et al. (2023)

Table 1 (continued)

Group of fed species	Source of waste given to sea cucumbers	Feed given to animals	Dry matter (%)	Crude protein (%)	Crude lipid (%)	Carbohydrate (%)	Ash (%)	Organic matter (%)	SGR (% d^{-1})	Source
Fish	Rainbow trout waste (*Oncorhynchus mykiss*)	ND[2]	98.68 ± 0.18	20.50 ± 0.86	3.29 ± 0.10	5.3 1 ± 0.08	70.90 ± 0.42	29.40*	0.90	Jin et al. (2016)
	Eel waste (ND)	ND[2]	98.2 ± 0.02	10.01 ± 0.86	1.14 ± 0.02	3.05 ± 0.06	85.80 ± 0.32	14.20*	0.86	Jin et al. (2016)

"Values provided are mean ± SE (unless indicated otherwise)." *ND* = no data, * = calculated. Carbohydrate was calculated as = 100 – (crude protein – crude lipid – ash). Numbers written in superscript represent the species of sea cucumber reared: [1]*Stichopus monotuberculatus*; [2]*Apostichopus japonicus*; [3]*Stichopus mollis*; [4]*Australostichopus mollis*, and [5]*Neostichopus grammatus* fed on aquaculture waste, *A. mollis* has the highest ingestion rate ingesting approximately 0.31 g g^{-1} d^{-1}. The range of the ingestion rate of sea cucumbers fed aquaculture waste quite compares with *A. japonicus* fed the combination of *Nitzschia closterium* and sea mud (0.18 g g^{-1} d^{-1}) and *Isostichopus badionotus* fed on the macroalgae *Solieria filiformis* (0.16 g g^{-1} d^{-1}), *Macrocytis piryfera* (0.15 g g^{-1} d^{-1}) and diatoms (0.06 g g^{-1} d^{-1}) (Martínez-Milián & Olvera-Novoa 2016; Shi et al. 2013, 2015). However, the range is lower than those of *A. japonicus* fed a combination of microalgae *Cylindrotheca fusiform* and sea mud; *C. fusiform* and yellow soil; diatom and sea mud with ingestion rates of 0.48, 0.52, 0.43, and 0.54 g g^{-1} d^{-1} respectively (Shi et al. 2013). The implication of the ingestion rate of sea cucumbers on solid waste reduction is that it determines the amount of waste the sea cucumbers would impact. It can be used to estimate the quantity and density of sea cucumber required for waste bioremediation. For example, Onomu et al. (2023) reported that an abalone farm produces an average sludge of about 2617 g m^{-2} yr^{-1}. All things being equal, approximately 14–15 *N. grammatus* of 17 g each, will be required to process all abalone solid waste produced per square meter per day from an abalone farm.

The IR of sea cucumbers is influenced by the nutrient content of food available to them. The nutrients contained in the food such as total organic matter (TOM), protein and energy influence the ingestion rate of sea cucumbers. There is an inverse relationship between IR and the TOM, protein and energy content in the food; i.e., the higher these nutrients, the lower the amount of food consumed (Hudson et al. 2004; Yuan et al. 2006) (Fig. 1). When food contains low amounts of these nutrients, sea cucumbers will ingest more of the food to meet their nutritional demand for growth (Fig. 1). Even in their natural environment, sea cucumbers exposed to sediments low in nutrients generally consume more sediment to meet their nutritional requirements. However, when the nutrient content of the sediment is high, the appetite of sea cucumbers is reduced; hence, they consume less (Azad et al. 2011; Hudson et al. 2004). Nevertheless, an exception to the increased food consumption response of sea cucumbers when provided with food containing low nutrient levels has been recorded. This arises when the nutrient level in the food is very low, reducing the palatability of the food; hence, sea cucumbers, in this instance, respond by decreasing their ingestion rate (Zamora and Jeffs 2012). For example, Zamora and Jeffs (2012) used mussel (*Perna canaliculus*) waste with varying amounts (1%, 4%, 12%, and 20%) of total organic matter (TOM) as feed for the sea cucumber (*A. mollis*). Sea cucumbers fed the 4% TOM diet had the highest ingestion rate, followed by those fed the 12% TOM diet, while those fed the 20% TOM diet had the lowest ingestion rate. Sea cucumbers fed a 1% TOM diet exhibited a low ingestion rate compared to the 4% TOM diet, possibly due to reduced nutrients in the feed resulting in low palatability (Zamora and Jeffs 2012).

However, Maxwell et al. (2009) showed that IR had a positive relationship between the feed's TOM, carbohydrate, and energy content, contrary to Zamora and Jeffs (2012) findings (Table 1). Maxwell et al. (2009) fed *S. mollis* with abalone food: Diet A (*Laminaria japonica* kelp flakes—organic matter: 76.40%; carbohydrate: 66.30%; energy: 14.07 J/mg), and two varieties of dried abalone faeces: Diet B and Diet C (Diet B—organic matter: 54.50%; carbohydrate: 35.00%; energy: 10.93 J/mg and Diet C—organic matter: 37%; carbohydrate: 21.30%; energy: 7.70 J/mg). The IR of *S. mollis* fed abalone faeces (Diet C) was 2.44 ± 0.62 mg and was lower than those fed Diets A and B. However, those fed abalone feed Diet A and Diet B had a similar IR.

Maxwell et al. (2009) proposed that the positive relationship between ingestion rate and organic matter content, which was contrary to studies available then, was because faecal diet and macroalgal diet were used in the study, whereas other studies available as of when theirs was conducted used natural sediment (Hauksson 1979; Hudson et al. 2004; Yingst

1982). Their supposition meant that IR being inversely proportional is only true when natural sediments are fed to sea cucumbers. However, studies on ingestion rate years after the study of Maxwell et al. (2009) show an inverse relationship even when sea cucumbers are fed with faecal waste (Chen et al. 2015b; Liu et al. 2010; Orozco et al. 2014; Yuan et al. 2006; Zamora & Jeffs 2011).

The lower ingestion rate reported for diet C compared to diets A and B of Maxwell et al. (2009) may be due to the aggregate effect of lower nutrient content in the diet, as the organic matter, carbohydrates and energy in diet C were the lowest of the diets presented. The reduced ingestion rate may likely be the exception to the rule of the inverse relationship between IR explained above when diets are very low in nutrients. The levels of the various nutrients contained in diet C may be perceived as "very low" for the species of sea cucumber thereby reducing the palatability of the diet. More research is needed regarding the levels of nutrients in diets that may be perceived as "very low" for various sea cucumber species.

Faecal production rate (FPR) and assimilation efficiency (AE)

The FPR is an important proxy tool used to ascertain feed consumption (Wotton and Malmqvist 2001). Faecal production rate is influenced by food availability, ingestion rate, food source, and the amount of food digested (Bureau and Hua 2010; Mente et al. 2011; Wotton and Malmqvist 2001). In sea cucumbers, FPR is affected by IR such that a high IR leads to a high FPR and vice versa. As previously stated, the ingestion rate is influenced by the nutrient content of the diet, such that a high-nutrient content leads to a low ingestion

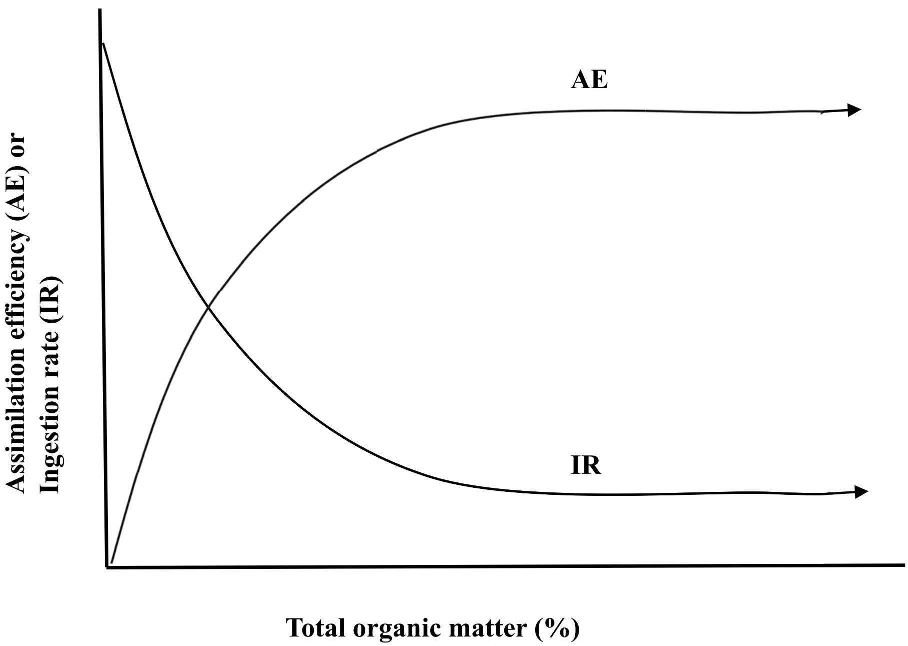

Fig. 1 Hypothetical assimilation efficiency (AE) and ingestion rate (IR) trend of sea cucumber in relation to total organic matter (TOM) in feed. **Source:** conceptualised by author

rate. For example, Chen et al. (2015b) fed *S. monotuberculatus* with combinations of fresh shrimp (*L. vannamei*) waste and mud mash with TOM's ranging from 16.61 to 46.53%. The three lowest TOM diets had the highest FPR. The result of Chen et al. (2015b) corresponds with the relationship between the ingestion rate and the faecal production rate mentioned above. A low TOM diet will lead to a higher IR which in turn leads to a higher FPR.

Similarly, when *A. mollis* was fed diets ranging from 1 to 20% TOM, the FPR of sea cucumber fed the 4% TOM diet had the highest faecal production rate followed by those fed 12% and those fed 20% (Zamora and Jeffs 2012). However, there is an exception to this rule of a low TOM in feed producing higher faecal output, which occurs when the TOM content of the feed is extremely low. In this instance, the feed becomes less palatable due to the reduced nutrient content; being reduced, and as such, the sea cucumber feeds less and produces fewer faeces (Zamora and Jeffs 2012). For example, in the experiment of Zamora & Jeffs (2012), the FPR of *A. mollis* fed the 1% TOM diet ought to be higher than those fed 4, 12, and 20% TOM. However, *A. mollis* fed the 4% TOM diet had the highest FPR, while those fed 1% TOM had a similar FPR to those fed the 12% TOM diet. The result of the faecal production of the 1% TOM diet being low corresponds with its IR, which was also low (Zamora and Jeffs 2012).

AE is the percentage of ingested feed absorbed/digested by the body and made available for metabolism (Ricker 1946). AE is also influenced by ingestion rate, faecal production rate and the nutrient content of the food (Maxwell et al. 2009; Zamora and Jeffs 2012). For example, *Cucumaria frondosa* assimilated 85% of salmon waste when used as feed (Nelson et al. 2012). Food containing high amounts of TOM results in a high AE and vice versa (Fig. 1). For instance, AE was lower when *S. mollis* was given a diet with 37% TOM compared to the 54.5% and 76.4% TOM diets (Maxwell et al. 2009). Similarly, in a study by (Zamora and Jeffs 2012), *A. mollis* were fed diets ranging from 1 to 20% TOM. Those fed 20% TOM had the highest AE, while there was no difference in the AE of sea cucumbers fed 4% and 12% TOM, which were higher than 1% TOM.

Survival, growth and feed conversion ratio (FCR)

Growth is an indicator of animal welfare, and impaired growth indicates poor welfare (Saraiva et al. 2019). Generally, sea cucumbers fed with aquatic animal waste have a high survival rate (Chen et al. 2015a; Mathieu-Resuge et al. 2020; Onomu et al. 2023; Slater et al. 2009). Animal waste results in better growth than sediments (sand and sea mud) from the natural environment of sea cucumbers and some macroalgae. Slater et al. (2009) reported that mussel waste fed to *A. mollis* is not only palatable to the sea cucumber but enhances its growth. The growth rate of *A. mollis* was investigated when fed with sediment; mussel waste at low, medium, and high quantities; and dried seaweed (*Sargassum polycystum*). The diets of the sediment and the low quantity of mussel waste exhibited negative growth rates. However, medium and high quantities of mussel waste and dried seaweed showed an increased SGR, with mussel waste (high) being significantly higher than others at 0.32% d^{-1} (±0.08 SD) over three months. Bell et al. (2007) reared *Holothuria scabra* in ponds previously used to rear shrimp; while no additional food was given during the culture period, the sea cucumbers increased from 12 to 400 g in 12 months. *H. scabra* fed with either shrimp waste or the seaweed *Navicula ramosissima* increased in weight, with those fed shrimp waste having the fastest growth (Watanabe et al. 2012).

Generally, a low level of protein and lipid is required for optimal growth in sea cucumbers (Huiling et al. 2004; Zhu et al. 2005). For example, Seo and Lee (2011) experimented to determine the appropriate dietary protein and lipid for *A. japonicus* using diets of 20, 30, and 40% crude protein with 2 or 10% lipids. *A. japonicus* fed feeds containing 20 and 40% protein with 2% lipid showed significantly higher growth (18%) compared to those fed a 30% protein with a 2% lipid diet. Similarly, Huiling et al. (2004) reported that 21% protein was required to support the growth of *A. japonicus*. However, for *S. japonicus*, an optimum dietary protein level of 18.21–24.18% and 5% crude lipid is reported as the dietary protein level that supports growth (Zhu et al. 2005). Sembiring et al. (2022) showed that *H. scabra*, fed with 20% crude protein, had a significantly higher SGR of 0.53% d^{-1} compared to 0.48 and 0.15% d^{-1} when fed 10% and 30% crude protein. The optimum protein required by *H. scabra* was reported to be 16.30% (Sembiring et al. 2022). Similarly, Broom et al. (2021) reported that *H. scabra* fed a diet of 14.5% crude protein and 4.5% lipid had a significantly higher specific growth rate of 1.30% d^{-1} unlike 0.44% d^{-1} and −0.58% d^{-1} recorded for 7.5% crude protein and 0.8% lipid and 5.5% crude protein and 0.6% lipid, respectively. The studies reported above showed that dietary protein of 2–21% is appropriate to support growth in *A. japonicus*. However, for *H. scabra*, a dietary protein of 14.5–20% and lipid of 4.5% may be appropriate to support growth.

Xia et al. (2015) conducted an experiment on the optimum dietary carbohydrate requirement for *A. japonicus*. Five carbohydrate levels were used in the feed, which were 25.61%, 34.55%, 45.3%, 55.82%, and 66.09%. Their result showed that SGR increased with increasing carbohydrate levels from 25.61 to 45.3%. However, increasing carbohydrate levels from 55.82 to 66.09% led to decreased SGR. They showed that a carbohydrate level of 48.56–49.30% was the optimum level to support growth in *A. japonicus*. This study shows that *A. japonicus*, like other aquatic animals, does not require very high levels of carbohydrates in feed. There is great uncertainty about the dietary requirements of carbohydrates for other sea cucumber species; this requires experimentation.

Animal waste alone may, however, not result in positive growth, especially when its nutrient content is inadequate to support growth. Yuan et al. (2006) showed that feeding *A. japonicus* with dried bivalve faeces resulted in negative specific growth (−0.66% d^{-1}). However, it should be noted that the bivalve faeces used in their study were oven-dried at 65 °C, and the nutritional value could have been affected by the drying process (Table 1). Oven-dried shrimp waste has also been used to grow *S. monotuberculatus*, although growth was not optimal compared to sea cucumbers fed oven-dried shrimp waste mixed with powdered algae and sea mud (Chen et al. 2015b). Domínguez-Godino and González-Wangüemert (2019) used sea bream faeces to feed *Holothuria arguinensis* at high (4 g) and low (2.5 g) rations; the SGR was negative for both. Jin et al. (2016) used eel waste, trout waste, and formulated pellet to feed *A. japonicus* and reported that sea cucumbers fed eel waste and trout waste had a poorer growth rate than those fed the formulated pellet. Similarly, Broom et al. (2021) reported a negative SGR of $-0.58 \pm 0.21\%$ d^{1} for *H. scabra* when fed on shrimp (*L. vannamei)* waste. The negative growth experienced by *H. scabra* could have been due to the shrimp faeces being sundried for a month; as such, the bacteria and dietary nutrients such as vitamins may have deteriorated (Broom et al. 2021). Due to the conflicting growth results obtained from animal waste alone, combinations of animal waste and other ingredients, such as seaweeds, have been used in an effort to enhance growth. Seaweed is notable in promoting the growth of Echinoderms like sea urchins (Onomu et al. 2020). As such, the idea of its use in a bid to enhance sea cucumber growth is not out of place. When Chen et al. (2015b) fed *S. monotuberculatus* with combinations of shrimp waste, sea mud, and *Sargassum polycystum*, sea cucumbers fed 75% shrimp waste, and 25% sea mud exhibited better growth compared to any of the other single diet treatments. In another study, a mixed diet of 25% shrimp faeces, 60% powdered algae, and 15% sea mud performed better than sea cucumbers fed shrimp faeces alone or the algae and seaweed (Chen et al. 2015a).

Similarly, Yuan et al. (2006) used various bivalve faecal waste and different combinations of faeces and seaweed (containing *Laminaria japonica*, *Sargassum thunbergii*, and *Sargassum* sp.) to feed the sea cucumber *A. japonicus.* Those fed a diet containing 75% faeces and 25% powdered algae had the highest SGR (2.13% d^{-1}). Mixed diets containing faeces tend to perform better in terms of growth than those fed on faeces or microalgae alone. This performance can be attributed to feed combinations, as mixed diets yield better growth compared to diets with a single ingredient (in other aquatic animals) (Coutteau 1996; Southgate 2003), and sea cucumbers are no exception. The role of fed aquatic animal waste in supporting sea cucumber growth in a mixed diet is important. It could be because waste from fed aquatic animals, especially marine animals, may provide some nutrients or mineral components essential for the metabolism of sea cucumbers (Xia et al. 2012). However, it should be noted that the appropriate combination of feed sources needs to be investigated on individual species of sea cucumbers.

Generally, aquaculture waste is known to have a low *C*:*N* ratio (not more than 10:1), which may not be sufficient to support growth (Robinson et al., 2019). Increasing the *C*:*N* ratio of aquaculture waste to about 20:1 has been reported to better support the growth of sea cucumbers especially *H. scabra*, unlike unsupplemented waste from aquaculture. In a study, abalone waste (*C*:*N* ratio of 5:1), D-glucose enriched abalone waste (*C*:*N*=20:1), starch enriched abalone waste (*C*:*N*=20:1) and cellulose microcrystalline enriched abalone waste (*C*:*N*=20:1) were fed to *H. scabra* for four months. At the end of the study period, sea cucumbers in all treatments had a 100% survival rate. Sea cucumbers reared on starch enriched abalone waste had significantly higher weight gain compared to those reared on abalone waste alone (Robinson et al., 2019). In a similar study by Senff et al., 2022), *H. scabra* were fed with waste from milkfish aquaculture, sludge supplemented with bagasse, and sludge supplemented with cellulose for 104 days. *Holothuria scabra*, fed sludge supplemented with bagasse, had significantly higher biomass weight. Sea cucumbers fed sludge with cellulose grew initially but exhibited negative growth afterwards.

The feed conversion ratio (FCR) is calculated from the weight of feed fed (dry) required to gain a unit of weight (wet) and is an indication of the performance of a feed (Besson et al. 2020), with a positive but low FCR being desirable. Some factors influencing the FCR include the animal's genetic makeup, age, management and feeding practices (Besson et al. 2020; Sultana et al. 2017). Chen et al. (2015b) reported that feeding 100% shrimp faeces resulted in the highest FCR when fed to *S. monotuberculatus*. Comparatively, the combined 25% shrimp waste and 75% formulated compound and the formulated compound alone resulted in the lowest feed efficiency. Yuan et al. (2006) showed that *A. japonicus* fed dried bivalve faeces alone had a negative feed efficiency as they lost weight, while those fed a mixture of 75% dried bivalve faeces and 25% powdered algae had the best feed efficiency (1.75).

Performance of sea cucumbers fed waste in IMTA: species selection and compatibility

For IMTA to be successful, knowledge of species with potential for coculture and a good culture system design are prerequisites. There should also be a balance in the biological and chemical processes, which can be achieved by appropriate species selection and ratios of the species under investigation. Determining the appropriate species and proportion should be done with care to prevent the potential stress and welfare of the species. Sea cucumbers have been cocultured with fish, sea urchins, shrimp, and molluscs.

Sea cucumber and abalone

Kang et al. (2003) cocultured *S. japonicus* with juvenile charm abalone (*H. discus hannai*). The abalone in the coculture group had a higher survival rate (96 ± 2%) compared to the abalone monoculture group (90 ± 2%), while there was no mortality of sea cucumbers during the study period. In addition, the coculture of sea cucumbers with abalone improved abalone growth by 145.71% compared to a 117.14% increase of abalone monoculture. The growth improvement was due to the reduced total ammonia nitrogen (TAN) and nitrate concentrations in the coculture group. *Apostichopus japonicus* was also cocultured with abalone (*H. discus hannai*) in abalone cages suspended from long lines (Qi et al. 2013). Abalone were fed kelp, while the sea cucumbers were not fed but had access to the abalone faeces. The survival rate was 100% for both species in coculture. Abalone and sea cucumbers in coculture had a 64.99% and a 90% weight increase, respectively.

The warty sea cucumber (*Apostichopus parvimensis*) and juvenile green abalone (*Haliotis fulgens*) were cocultured at a medium sea cucumber density of 2:1 (abalone: sea cucumber) and a high sea cucumber density of 1:1 (Bauer et al. 2019). However, abalone in the medium sea cucumber density had 18% greater growth in shell length than those in the high sea cucumber density group and 29% higher shell length than abalone in the monoculture group. The growth of sea cucumbers showed variation; their size had increased two weeks into the trial, but by week four, there had been a reduction in their wet weight. However, the wet weight of the sea cucumbers dropped in week eight and remained poor until the end of the study. The negative growth experienced by the sea cucumbers in this coculture experiment was due to spawning events that occur naturally in this species (Bauer et al. 2019). During the spawning period of sea cucumbers, they are known to reabsorb their gonads and cease feeding, leading to a reduced body weight (Espinoza-Montes 2000). The coculture of sea cucumber with abalone is viable with high rates of abalone and sea cucumber survival and improved growth of the abalone (Fang et al. 2009; Jin et al. 2011; Kang et al. 2003; Nam et al. 2011; Qi et al. 2013; Xia et al. 2017).

Onomu et al. (2024b) reported that the sea cucumber *N. grammatus* improves the growth of abalone (*Halistis midae*) in IMTA; however, the increase in abalone growth is dependent on the sea cucumber density. In another study, Onomu et al. (2023) stated that the presence of sea cucumber *N. grammatus* in abalone *Haliotis midae* production tanks leads to reduced tank cleaning frequencies without negatively impacting the water quality and growth of abalone. However, a reduction in the weight of the sea cucumbers was reported. Further studies by Onomu et al. (2024a, b& 2025b) showed that the growth of *N. grammatus* is influenced by the tank rearing condition, i.e., the presence of sand substrate and water temperature. This possibly could be the reason for the negative growth experienced in *N. grammatus* monoculture or coculture with abalone.

Sea cucumber and shrimp

The outbreak of disease is a significant problem in shrimp aquaculture, making it a high-risk venture, and it is often caused by poor water quality (Pitt et al. 2004). An example is the high ammonia concentration associated with shrimp culture due to excretion by shrimp and the decomposition of their faeces (Martin et al. 1998). Some shrimp ponds are left empty for periods of the year or have been abandoned due to economic failure after disease outbreaks, making farmers search for either an extra or an alternate species or different culture systems (Pitt et al. 2004). These have propelled the coculture of shrimp with other species, such as sea cucumbers, or the periodical stocking of sea cucumbers instead of shrimp in abandoned ponds and during periods of pond fallowing in a bid to improve water quality and maximise profit.

The polyculture of sea cucumber, especially *H. scabra*, and shrimp may not be viable as it is associated with adverse outcomes, such as poor growth and very poor water quality, unlike the monoculture of either species (Bell et al. 2007; Purcell et al. 2006). High mortality of either or both animals in culture has been reported and ascribed to stress (Bell et al. 2007). Also, shrimps feed on or damage the skin of juvenile *H. scabra* in particular (Bell et al. 2007; Pitt et al. 2004). *Holothuria scabra* may also serve as an alternative food for shrimp when there is insufficient food in the culture system, and shrimp can induce evisceration in *H. scabra* and then feed on the viscera (Pitt et al. 2004). It is possible that larger *H. scabra* may not experience the same level of harassment from shrimp in coculture.

However, the coculture of sea cucumber and shrimp generally has no adverse effect on the shrimp, nor does it lead to improved growth in shrimp as reported for some other animals (Chogale et al. 2016; Purcell et al. 2006; Zhou et al. 2017a, b). However, the survival and growth of sea cucumbers are usually compromised in coculture with shrimp. Bell et al. (2007) and Purcell et al. (2006) both reported that the survival and growth of *H. scabra* were lower in polyculture with shrimp (*L. stylirostris*) than in monoculture. Conversely, Zhou et al. (2017a, b) reported that the sea cucumber, *A. japonicus*, survived better and grew faster in coculture with shrimp (*Fenneropenaeus chinensis*) at low densities than when grown in monoculture. Zhou et al. (2017a, b) reported that *F. chinensis* showed no aggressive behaviour towards low densities of *A. japonicus* and that it was viable to coculture them in an earthen pond system.

Though sea cucumbers have been reported to effectively reduce organic matter, organic carbon, and inorganic nitrogen in the culture system due to their feeding habit, thereby improving the water quality (Chogale et al. 2016; Kang et al. 2003; Yu et al. 2016), Purcell et al. (2006) showed that shrimp coculture of the *L. stylirostris* with *H. scabra* did not improve water quality as the ammonium-nitrogen in the coculture system was significantly higher than in the monoculture system. That being said, the coculture of sea cucumber and shrimp can reduce phytoplankton's productivity in the culture system (Yu et al. 2016). Overall, this suggests that shrimp species selection and possibly sea cucumber species and size must first be better understood before shrimp-sea cucumber coculture can be optimised.

Sea cucumber and filter-feeding bivalves

Sea cucumbers have been found naturally on oyster ropes and underneath oyster farms, attracting interest in the species being cocultured (Paltzat et al. 2008). An IMTA trial of the sea cucumber *A. mollis* with the Pacific oyster (*C. gigas*) was conducted in an open cage by Zamora et al. (2014), with sea cucumbers almost doubling their weight within the first six months (SGR: 0.4% d^{-1}). However, after that, there was a decrease in the weight of the sea cucumbers, possibly due to changes in water temperature or increased stocking density (Zamora et al. 2014). The survival rate of sea cucumbers was difficult to ascertain because some were lost during the experiment. Paltzat et al. (2008) also cocultured *C. gigas* with the sea cucumber *Parastichopus californicus* for 12 months in trays underneath oyster rafts. The survival rate of sea cucumbers was 100%, while their average SGR ranged from 0.061 to 0.158% d^{-1}. Yokoyama (2015) cultured *A. japonicus* below *C. gigas* rafts and reported a 100% survival rate of sea cucumbers, whereas *A. japonicus* grew from 0.08 ± 0.01 g to 5.5 ± 1.2 g in 216 days with an SGR of 2% d^{-1}. These studies showed that sea cucumber culture below oyster rafts is viable and can effectively utilise faecal waste and sediments around oyster farms as food. There, however, is a paucity of information from controlled feeding experiments where oyster solid waste is provided to sea cucumbers.

Hannah et al., 2012) reared *P. californicus* in cages and were fed on a natural diet for 12 months, resulting in an SGR of 0.267% d^{-1}. Slater and Carton (2007) studied the suitability of culturing *A. mollis* underneath a mussel farm for six months, which resulted in a 91.7% survival of *A. mollis*. Sea cucumbers caged at 2.5 ind m^{-2} and 5 ind m^{-2} increased in weight by 15.37% and 13.16%, respectively, while those at 15 ind m^{-2} had a 0.21% reduction in weight. The reduction in weight at the high stocking density was attributed to food limitations and competition (Slater & Carton 2007). Ren et al. (2012) cocultured *A. japonicus* with the scallop *C. farreri* in a pond for a year. Sea cucumbers in the coculture grew by 115.5% compared to 83.7% of those in monoculture. There was, however, no difference in scallop growth or survival between the coculture and monoculture treatments. Sea cucumber mortality was high in summer due to the high-water temperature and rainfall, reducing water salinity. *S. japonicus*, growth increased from 17.3 ± 2.5 g ind^{-1} to 34.0 ± 5.4 g ind^{-1} within seven weeks with an average SGR of 1.38% when cocultured with *C. farreri* in a flow-through system (Zhou et al. 2006).

In another experiment, Zhou et al. (2006) cocultured *S. japonicus* with bay scallop (*A. irradians*) and Zhikong scallop (*C. farreri*) in lantern nets suspended under long lines. Both scallops and sea cucumbers grew well and suffered low mortality. There was no difference in the survival and growth of scallops in the monoculture and the coculture methods. The wet weight of sea cucumbers cocultured with scallops increased from 16.1 ± 2.4 g ind^{-1} to 30.6 ± 6.4 g ind^{-1} after 12 weeks at an average SGR of 0.31% d^{-1}.

These studies reflect that the coculture of scallops and sea cucumbers performs comparably with each species' monoculture in land-based or offshore systems. Scallops (*C. farreri* and *A. irradians*) survive well with sea cucumber (*A. japonicus* and *S. japonicus*), where the presence of one does not hinder the growth of the other. Although coculturing these species may not improve the growth of either species, both serve as a means of diversification and space maximisation leading to greater profitability.

Sea cucumber and fish

Limited information on rearing sea cucumbers and fish in the same culture unit on land is available. This may be due to compatibility issues, as fish cannot be confined like shellfish and may move to the bottom of the culture system, where they may interfere with the sea cucumbers. The culture of sea cucumbers beneath fish net pens and cages is viable and has shown high survival and growth rates for sea cucumbers. For example, *A. japonicus* was cultured in an IMTA environment with crimson snapper (*Lutjanus erythopterus*), blue-spotted grouper (*Epinephelus fario*), and cobia (*Rachycentron canadum*) and had an SGR ranging from 0.40 to 0.71% d^{-1} with a 100% survival during winter and early spring (Yu et al. 2014). However, during summer, negative SGR ranging from -0.4 to -1.2% d^{-1} and mass mortality were experienced due to aestivation and anoxia (Yu et al. 2014).

Also, Hannah et al. (2013) cultivated *P. californicus* in suspended culture underneath net pens of sablefish (*Anoplopoma fimbria*) at an IMTA site for 12 months. Juvenile sea cucumbers had a high survival rate (99.5%) and an SGR of 0.1% d^{-1} both in the field and control sites. Similarly, juveniles of *A. japonicus* reared beneath red sea bream (*Pagrus major*) fish cages for 238 days showed a high survival rate of 96% and an SGR of 1.9% d^{-1} (Yokoyama 2013). After 307 days, the sea cucumbers grew to a marketable size (mean wet weight = 142–181 g). Similarly, sea cucumbers reared in the effluent of milk fish (*Chanos chanos*) in a recirculatory aquaculture system (RAS) for 70 days had a 100% survival rate. The SGR of the sea cucumber and the milkfish were $1.1 \pm 0.7\%$ d^{-1} and $1.1 \pm 0.1\%$ d^{-1}, respectively (Senff et al., 2020).

Besides sea cucumbers being able to utilise fish faeces as food and gain biomass, sea cucumbers, through their feeding action, also reduce the organic matter, carbon, and nitrogen content of sediment from fish faeces. This has been reported for sea bream (*Sparus aurata*) and sea bass (*Dicentrarchus labrax*) (MacDonald et al. 2013; Neofitou et al. 2019; Hannah et al. 2013).

Economic benefits of waste from fed aquaculture as a food source and its associated risk

Feed is one of the most expensive components of an aquaculture operation, accounting for up to 60% of the cost of production (Gabriel et al. 2007; O'Donncha & Grant 2019; Onomu & Okuthe 2024b). Reducing the cost associated with animal feed without compromising the animals' growth would be advantageous to aquaculturists (Onomu & Okuthe 2024a, b). Faecal waste from fed aquaculture animals, which otherwise would have been flushed out from the system, has been shown to be beneficial to sea cucumbers, leading to good growth rates, thus reducing the cost of feeding; hence the cost of production. Using faecal waste from fed aquaculture as feed for sea cucumbers is also beneficial to the aquatic ecosystem, which often remains the dumping ground for aquaculture waste (Onomu et al. 2023). This is because sea cucumbers are able to utilise nutrients in the faeces and build up body mass, thereby reducing the nutrient load (nitrogen, carbon, and total organic matter) that would have been discarded into the natural environment, thus making aquaculture more environmentally sustainable (Neofitou et al. 2019; Ren et al. 2012; Slater et al. 2009). Though sea cucumbers are able to reduce the nutrient load of aquaculture waste, their actual impact on the waste is density-dependent. The density of sea cucumbers needed for growth and bioremediation may differ, with that for effective remediation being somewhat higher (Chary et al., 2020); Onomu et al., 2025a; Namukose et al. 2016). Further research is required on the optimal density to support growth and bioremediation.

Regardless of the benefits derived from using faecal waste as feed, the possibility of faecal waste being vectors of diseases and parasites to sea cucumbers and vice versa should also not be overlooked.

Conclusion and recommendations

One of the benefits of IMTA includes the yield of additional income from the extractive species. For this to be attained, it becomes necessary that the species of sea cucumbers are first fed with the waste of the animals to be cocultured to ascertain the acceptability, growth, survival, welfare, and health of the sea cucumbers when fed on the waste. This is where appraising the use of waste from fed aquaculture species as food comes into play.

A variety of sea cucumber species have been shown to consume waste from fed aquatic animals. Various studies available on the use of waste as feed show that waste contains nutrients that support growth and survival of sea cucumbers and have no detrimental effect on the welfare of sea cucumbers.

The benefits of waste as feed cannot be overemphasised. These wastes would otherwise have been discarded, but value is added to them by converting as feed to grow sea cucumbers which are of economic importance. Subsequently, the nutrient load of the culture tank and the effluent flushed out is reduced; thus, its impact on the receiving environment is also curtailed, which addresses one of the sustainability issues associated with aquaculture.

Feed is one of the most expensive aquaculture components and forms the bulk of the cost expended in aquaculture. The use of waste from fed aquaculture animals as feed for sea cucumbers increases profitability as sea cucumbers are grown at little/no added cost of production.

Where the IMTA of sea cucumbers and other aquatic animals are not feasible due to incompatibility, waste collection is encouraged. Sea cucumbers can also be integrated directly to the place where faeces settle when the waste from the culture system is flushed, especially when the efficacy of the waste has been proven. Where wastes cannot optimise growth, it is recommended that some other rich ingredients be added as a supplement.

Though the benefits derived from waste are numerous, waste from fed aquaculture animals being potential vectors of diseases and thus leading to biosecurity issues should not be overlooked. Even in IMTA, diseases may be spread from the fed species to the sea cucumbers and vice versa. Consumers need to be assured that sea cucumbers fed on waste are healthy for consumption. Hence, further studies need to be done on the health implications of feeding animal waste to sea cucumbers and the potential risk associated (if any) with human consumption of sea cucumbers fed with animal waste.

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Declarations

Competing interests The authors declare no competing interests.

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