International Journal of Environmental Science and Technology (2019) 16:4059–4068
https://doi.org/10.1007/s13762-018-2051-x

ORIGINAL PAPER

Evaluation of post-consumer food waste as partial replacement of commercial feed in marbled rabbitfish, *Siganus rivulatus* aquaculture

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Received: 5 April 2018 / Revised: 2 September 2018 / Accepted: 4 October 2018 / Published online: 10 October 2018

Abstract
Food waste remains as one of the most serious environmental challenges facing the world today, with sizable quantities generated and disposed of in landfills. Accordingly, exploring solutions to mitigate the detrimental impacts of such waste becomes vital. Aquaculture, a rapidly growing industry in rural areas of developing nations, offers the potential of using this waste productively to partially replace commercial feed, which is often absent or expensive. The present study delves into new options of using plate food waste collected from local restaurants as fish feed supplementation. Food waste, collected and processed into pellets, was evaluated in an 8-week feeding trial of rabbitfish, *Siganus rivulatus*. Five feeding regimens were adopted in which commercial feed was substituted with waste-based feed at 0, 25, 50, 75 and 100% of daily offering. Results suggest that up to 73.2% of the commercial feed can be substituted by waste-based feed with no significant effects on survival, growth rate, feed conversion ratio, or hepatosomatic and viscerosomatic indices of the fish. There were no statistical differences among treatments with 0, 25 and 50% replacement in terms of whole-body protein and lipid content or in hematological parameters. However, at 75% substitution, there was a clear decrease in growth, whereas at 100% replacement the fish showed complete mortality. Therefore, this study demonstrates a potential solution to mitigate food waste from landfills by utilizing it as a partial replacement of commercial fish feed. This in turn decreases the cost incurred in aquaculture production.

Keywords Fish feed · Plate food waste · Post-consumer food waste · Recycling

Introduction

Food spoilage and food waste have always been among the most challenging predicaments of humankind. In recent years, governmental and non-governmental organizations have drawn attention to lost or wasted foods and their implications on food security, sustainability and the environment. In fact, food loss and food waste are major ethical dilemmas as demand for food increases worldwide (FAO 2014) and yet more than 925 million people continue to suffer from undernourishment (Gustavsson et al. 2011).Various waste management strategies and guidelines have emerged with the “food waste hierarchy” provided by the EU (European Union) being the most prominent. This food waste hierarchy prioritizes the efforts to reduce the amount of waste generated by households, industries and governmental sectors; reuse of surplus food resources for human consumption; recycle food waste into useful material such as animal feed or compost; and recover energy by means of anaerobic digestion (EC 1975).

Food waste generated at various levels of the food supply chain is attracting a lot of attention because of its environmental, social and economic impacts (Mourad 2016). Food waste management faces many challenges because of the negative impacts such as despoliation of natural resources, i.e., *soil nutrients, water and energy* (Rockström et al. 2009);

Editorial responsibility: Binbin Huang.

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cost for waste management (Gustavsson et al. 2011); impact on greenhouse gases from the early stages of food production through spoilage (Padfield et al. 2012); dumping in landfills (FAO 2014); and social implications in relation to food security issues (Parfitt et al. 2010). Accordingly, several food waste management processes are being considered while maintaining the notion that food waste can be a valuable resource (Bringezu and Bleischwitz 2017).

Most food waste mitigation programs recommend the use of a food recovery hierarchy which stipulates:(1) food waste prevention by decreasing excess at the source, improving processing technologies and adjusting production to needs; (2) reallocation of excess food to people in need (e.g., charity and social accountability); and finally (3) recycling food waste to produce animal feed, energy or fertilizers (EC 1975; FAO 2013). Some experts suggest that recovery and recycling of food waste are not as efficient as waste prevention in diminishing such wastes (Lorek and Spangenberg 2014; Tukker et al. 2017). Nevertheless, most work on food loss prevention focuses on the bottom of the hierarchy (i.e., recycling), because prevention and recovery are typically difficult to measure and more indefinite in relation to environmental impacts (Eriksson et al. 2015). Additionally, social and economic criteria should be taken into consideration when deciding on a waste management plan, especially since patterns of global food waste suggest a direct relationship between the economic status of a region/country, the quantities of food lost/wasted, and the stage of the food supply chain at which they occur. Developing countries or low-income nations experience more food loss in the early stages of the food supply chain (production and post-harvesting), while in industrialized or high-income countries higher waste occurs during processing, retail and consumption (Papargyropoulou et al. 2014). Accordingly, the waste hierarchy is used as a flexible guideline for setting waste management plans and not a prescription to end all problems (Porter 2010; Price and Joseph 2000; Rasmussen et al. 2005). The choice of which food waste management strategy to implement depends on the desired outcomes whether to protect the environment, enhance trade and profit (economic), and/or improve food availability (social). Under the environmental hierarchy, the most promoted solutions are ranked within recycling and include among many suggestions the reuse of food waste as animal feed (Mourad 2016; Salemdeeb et al. 2017). A major advantage of such recycling is keeping food waste away from landfills while using it productively.

Post-consumer food waste is mainly comprised of food plate leftovers or food purchased but not consumed. It often includes non-consumable components such as eggshells, pineapple skin, apple cores, bones and coffee grounds in addition to a substantial quantity of protein, lipids and carbohydrates. In other words, food waste includes quality food along the value chain suitable for human consumption but ultimately unconsumed and/or discarded (Gustavsson et al. 2011). Other factors such as cooking practices, demand anticipation, food quality, expiry dates and menu choices also contribute to food waste (Monier et al. 2010; Priefer et al. 2013).

Aquaculture is the fastest growing sector of animal production which requires *circa* 75 million tons of prepared feed annually amounting to approximately 250–300 million tons of fresh ingredients. Commercial feeds tend to be quite expensive partly because of a necessary uniformity of feeds in terms of nutritional content, consistency in form, and practicality of use. Feed accounts for more than 50% of production costs in aquaculture (Chong 1993), often reaching 80% of operation costs of a fish farm. Thus, any scheme that reduces feed cost without affecting fish production is welcome.

A major concern with residential and restaurant trash as well as expired foods at supermarkets and agricultural processing wastes is that they are often not a complete nutrient source for eukaryotic organisms. Frequently, wastes are mixed with other sources of nutrition such as fishmeal, vitamins and minerals and processed into fish feed. This is difficult in developing nations where most fish farming takes place. Moreover, fish tend to conserve essential amino acids and other nutrients for necessary body building blocks and use non-essential nutrients for metabolism and energy. Accordingly, we postulate that farmers can offer their fish a feed containing complete dietary necessities in order to supply essential nutrients and then offer processed wastes to supplement caloric needs. Thus, farmers could use recycled waste to supplant expensive feed without deleterious effects. The processed wastes can be produced locally, thus saving on shipping and storage as well as reducing fish production costs. To the best of our knowledge, the majority of existing studies have only focused on utilizing vegetable waste from farms and food processing industry to produce animal feed for swine (San Martin et al. 2016), but limited operations are those focusing on fish feed and fish production (Cheng et al. 2016; Choi et al. 2016).

The present work assesses whether post-consumer food waste could be used to supplant diets of marbled rabbitfish (*Siganus rivulatus*), an algaevorous marine fish native to the West Indian Ocean region and the Red Sea (Forsskal 1775). Marbled rabbitfish is an economically valuable species with growing interest for aquaculture in Eastern Mediterranean countries (El-Dakar et al. 2011; Saoud et al. 2008b). Several qualities make *S. rivulatus* good candidates for aquaculture such as being eurythermal and euryhaline (Saoud et al. 2007, 2008a) in addition to their tolerance to high stocking densities (Saoud et al. 2008b). Although *S. rivulatus* are algaevorous in nature, they readily accept artificial feed when raised in culture systems (Abou-Daoud et al. 2014; Barakat et al. 2011; El-Dakar et al. 2011). The present study evaluates the use of restaurant food discards as partial replacement of commercial fish feed on survival, growth, feed conversion, hematology and proximate composition of marbled rabbitfish. The work was performed at the aquaculture research laboratory of the American University of Beirut (AUB), Lebanon, between October and December 2016.

Materials and methods

Waste collection and feed processing

Post-consumer restaurant food waste was collected in the period extending between June and July 2016 from local restaurants serving traditional Lebanese–Mediterranean food. The collected waste was sorted, ground and then dried at 70 ± 5 °C in a forced-air oven to a moisture content of 6 ± 1%. Following drying, the samples were further pulverized to 50 µm using a burr grinder and stored at room temperature in vacuum-sealed bags.

In order to determine the proper mix that will provide the desired water stability of the fish feed, the samples were extruded and tested after mixing with a variety of gelatinizing ingredients such as wheat flour or cellulose (Vitacel R 200® J. Rettenmaier & Söhne GmbH & Co. KG, Rosenberg, Germany). The diet with a ratio of 4:1—food waste to cellulose—was then selected as it provided the longest water stability for at least 10 min. Accordingly, the fish feed was prepared and extruded using a Model BD-GP50 (Henan Bedo Machinery Equipment Co., Ltd, China) extruder. The resulting pellets were dried at 40 °C to a moisture content of 8% and stored at − 20 °C. A commercial fish feed (Rangen 35; Rangen Inc., Buhl, Idaho, USA) was ground to match the size of the locally prepared feed pellets and used as the control diet.

Proximate composition

Proximate composition of feeds and fish was performed as described in Nasser et al. (2018). This includes the measurement of moisture, total nitrogen, crude protein, fiber, ash, carbohydrate, lipid, carbohydrate-to-lipid ratio, energy, protein-to-energy ratio and protein solubility. Following the proximate analysis, the digestible energy in the feeds was calculated as 16.72, 17.62 and 37.62 kJ/g for protein, carbohydrate and lipid, respectively (Garling Jr and Wilson 1976).

Fish experiment

The university animal care approval was obtained prior to fish handling. Juvenile marbled rabbitfish were caught from the wild and quarantined for 1 month in a recirculating saltwater system connected to a biological filter and a pump. The fish were offered a 36% protein and 6% crude lipid commercial feed (Rangen Inc., Buhl, Idaho, USA) twice daily.

The experiment was performed in fifteen 180-L fiberglass tanks (60 × 60 × 50 cm) connected to a biological filter and settling tank. Water was aerated using a regenerative blower with submerged air diffusers. The temperature in the tanks was maintained at 26–28 °C using submerged heating elements. Salinity, temperature and dissolved oxygen were monitored daily using a handheld YSI Model 85 dissolved oxygen (DO) meter (YSI Inc., Yellow Springs, OH, USA), whereas the total ammonia nitrogen (TAN), nitrite nitrogen and pH were measured weekly using a HACH saltwater aquaculture test kit, Model FF-3. The photoperiod during the duration of the experiment was maintained at 14:10 h (light/dark), and 30% of the water in each system was exchanged weekly or as necessary to maintain the optimal water quality.

The fish used in the experiment were size-sorted by hand, and 15 fish 7.5 ± 1.46 g per fish (mean ± SD) were randomly stocked into each of the 15 tanks. The fish were offered one of five feed regimens with three replicate tanks per treatment where the treatments are as follows:

(i) T1: 100% commercial feed (CF);
(ii) T2: 75% CF and 25% waste-based feed (WBF);
(iii) T3: 50% CF, 50% WBF;
(iv) T4: 25% CF, 75% WBF; and
(v) T5: 100% WBF.

The feed offered to the fish was measured as 5% of total body weight divided into four daily portions over 12 h (7:00 h, 11:00 h, 15:00 h and 19:00 h) over a period of 6 days per week. The commercial feed was always offered in the morning followed by WBF whenever applicable. For example, in treatment T2 (75% CF, 25% WBF) the first three portions were CF, whereas the fourth was WBF. The feed ratio was increased by 10% on weeks when biomass was not measured. The fish were group-weighed biweekly following a day of fasting and the feed ration was adjusted accordingly (5% of the average total biomass of the largest treatment). The experiment was terminated after 8 weeks.

Fish performance

At termination, the fish were fasted for 24 h prior to data collection. Accordingly, the fish were anesthetized using a solution of MS 222 (Western Chemical Inc., Washington, USA) and group-weighed. The individual weight and length of each fish were also measured. Fulton's condition index (K), survival rate reported in % and feed conversion ratio were calculated according to Eqs. (1), (2) and (3), respectively.

$$K = \frac{M}{L^3} \times 10^5 \tag{1}$$

where M is mass (g) and L is length (mm)

$$S = \left(\frac{\text{No. of fish at end of experiment}}{\text{No. of fish at beginning of experiment}}\right) \times 100 \quad (2)$$

$$\text{FCR} = \frac{\text{Total mass of feed provided}}{\text{Final biomass} - \text{initial biomass}} \quad (3)$$

Fish hematology and proximate composition

Blood samples were collected by cardiac puncture using heparinized 1-ml syringes with 20 gauge 4 cm needles. At least four samples were taken from each tank. All hematology tests were performed as described in Nasser et al. (2018). The parameters tested include hematocrit (HCT), total plasma protein (TPP) (g/dL), and hemoglobin (HB) (g/dL). Differential white blood cells (WBCs) counts were also performed on blood smears that were fixed with absolute ethanol and stained with Wright-Giemsa stains (Vázquez and Guerrero 2007). Eight hundred cells were counted on each slide in areas with no extensive overlap of cells.

Following blood extraction, the fish were weighed and subsequently the liver and viscera were removed and weighed. The hepatosomatic (HSI) and viscerosomatic (VSI) indices, reported as a percentage, were calculated as per Eqs. (4) and (5), respectively.

$$\text{HSI} = \frac{\text{Liver Mass (g)}}{\text{Body Mass (g)}} \times 100 \quad (4)$$

$$\text{VSI} = \frac{\text{Viscera Mass (g)}}{\text{Body Mass (g)}} \times 100 \quad (5)$$

In addition, four fish from each tank were also macerated and dried in an oven at 95 °C to constant mass. These samples were stored for proximate analysis which was performed following the procedures described in Nasser et al. (2018).

Statistical analysis

Results were analyzed using SAS (V.9.2, SAS Institute Inc., Cary, NC, USA). A simple analysis of variance (ANOVA) was used to compare means of all parameters tested followed when necessary by a Student–Newman–Keuls (SNK) means separation test to determine significant differences among treatments means. Significance was at $p < 0.05$.

Results and discussion

Water quality parameters remained within narrow ranges throughout the experiment with reported temperature of 25.4 ± 1.1 °C; salinity 35.7 ± 1.5 ppt; pH 7.9 ± 0.12; and dissolved oxygen (DO) of 6.65 ± 0.49 ppm—(mean ± SD). These parameters are all within optimal ranges for marbled rabbitfish.

Proximate compositions of the commercial and waste-based feeds used in the present work are summarized in Table 1. The commercial feed had almost twice the protein content of the waste-based feed: 40.7 versus 18.9%, respectively. Conversely, the waste-based feed contained around four times more lipids than the commercial feed: 22.2 versus 5.2%, respectively. Although both feeds were iso-energetic (20 kJ per g of diet), they had different amounts of digestible energy, ash and fiber.

The fish in all treatments gained weight and length during the first 4 weeks. At that point, the fish in treatment T5 which were offered 100% WBF started exhibiting a significant decrease in growth and started dying (Fig. 1; Table 2). A breakpoint analysis of growth (Fig. 2) reveals a breakpoint of 73.2% feed replacement. The equations of the two best fit models are given by Eqs. (6) and (7)

$$y = -0.038 \cdot x + 22.34 \quad \text{with} \quad R^2 = 0.709 \quad (6)$$

$$y = -0.728 \cdot x + 72.87 \quad \text{with} \quad R^2 = 0.997 \quad (7)$$

where y is average weight (g) and x is the percent replacement of WBF.

Mean values of the final body weight (FBW), final length (FL), FCR and HSI showed significant differences among

Table 1 Proximate composition of the experimental diets (mean ± SD) used to feed *Siganus rivulatus* juveniles over 8 weeks

Proximate composition	Commercial feed	Waste-based feed
Dry matter (%)	93.4 ± 0.4	93.7 ± 0.6
Ash (%)	7.5 ± 0.26	5.5 ± 0.46
Crude protein (%)	40.7 ± 0.57	18.9 ± 0.4
Lipid (%)	5.2 ± 0.33	22.2 ± 4.80
Fiber (%)	4.6 ± 0.1	15.3 ± 0.7
Carbohydrates (%)[a]	35.4	31.8
CHO/L ratio[b]	7.6	2.1
P:E (g/MJ)[c]	2034.0	901.7
Protein solubility (%)[d]	9.3 ± 1.70	8.3 ± 0.87
Gross energy (MJ/kg)	20.01 ± 0.16	20.96 ± 0.19
Digestible energy (MJ/kg)[e]	14.99	17.11
CP/DE (g/MJ)[f]	27.15	11.05

[a]Carbohydrates (%) = 100 − (crude protein% + crude lipid% + moisture% + ash% + fiber%)

[b]Carbohydrates-to-lipid (CHO:L) ratio = mass% in CHO: mass% in lipid

[c]Protein to energy ratio (P/E) (mg/kJ) calculated as: [Crude Protein]/[Energy]

[d]Protein solubility (%) = protein in KOH/protein in sample × 100%

[e]Digestible energy (Garling Jr and Wilson 1976)

[f]Crude protein to digestible energy NRC (1993)

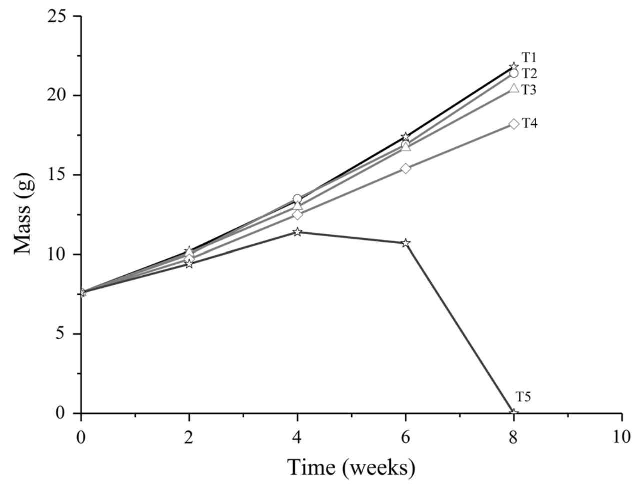

Fig. 1 Growth in average individual body weight (g) of juvenile *Siganus rivulatus* fed with increasing % of waste-based feed (WBF) over 8 weeks; T1: 100% commercial feed (CF); T2: 75% CF and 25% waste-based feed (WBF); T3: 50% CF 50% WBF; T4: 25% CF, 75% WBF; and T5: 100% WBF

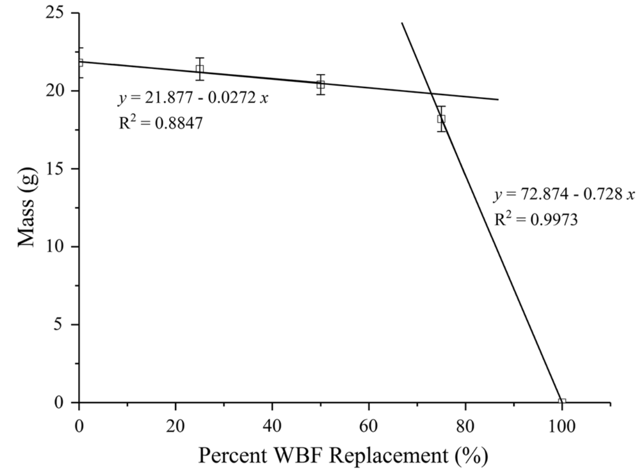

Fig. 2 Breakpoint analysis of average growth (g) of juvenile *Siganus rivulatus* as a function of % replacement of commercial feed by waste-based feed (WBF) over 8 weeks

treatments (p value < 0.05). However, K and VSI were not significantly different (p value > 0.05) among the treatments. FBW and FL of treatment T4, 18.2 ± 4.22 g (mean $\pm$ SD) and 11.25 ± 0.79 cm, respectively, were different from all other treatments. Furthermore, treatment T4 had the greatest FCR (2.43 ± 0.15). Protein and energy retention or efficiency are not reported because in most treatments except treatment T1, fish were offered excess feed in order to eliminate the possibility that growth differences would be the result of food limitation.

There were no significant differences in hemoglobin and total plasma protein among the treatments (Table 3). Hemoglobin mean values ranged between 11.47 and 13.14 g/dL, while TPP varied between 4.06 and 4.27 g/dL. Hematocrit values were significantly different among treatments with treatment 4 having the smallest mean of 24.06 ± 2.66%. No differences were noted in the differential white blood cell

Table 3 Hemoglobin (Hb; g/dL), hematocrit (HCT; %) and total plasma protein (TPP; g/dL) of juvenile *Siganus rivulatus* fed with increasing % of waste-based feed (WBF)

Treatment	HB	HCT	TPP
CF 100% (T1)	13.14[a]	28.83[a]	4.27[a]
WBF 25% (T2)	12.84[a]	28.07[a]	4.06[a]
WBF 50% (T3)	11.86[a]	27.59[a]	4.24[a]
WBF 75% (T4)	11.47[a]	24.06[b]	4.19[a]
WBF 100% (T5)	N/A*	N/A*	N/A*
PSE	0.50	0.97	1.43

Values in the same column with different superscripts (a, b) are significantly different from each other ($p < 0.05$)

PSE pooled standard error

*Mortality in treatment 5 was 100%. Accordingly, no data were available for the studied parameters

Table 2 Survival (S; %), final body weight (FBW, g), final length (FL, cm), Fulton's condition index at harvest (K), feed conversion ratio (FCR) and hepatosomatic (HSI, %) and viscerosomatic (VSI, %) indices of juvenile *Siganus rivulatus*

Treatment	S	FBW	FL	K	FCR	HSI	VSI
CF 100% (T1)	97.8[a]	21.7[a]	11.87[a]	1.27[a]	1.93[a]	2.21[a]	11.80[a]
WBF 25% (T2)	97.8[a]	21.4[a]	11.83[a]	1.26[a]	1.97[a]	2.42[a,b]	12.30[a]
WBF 50% (T3)	97.8[a]	20.5[a]	11.73[a]	1.26[a]	2.03[a]	2.44[a,b]	12.29[a]
WBF 75% (T4)	100[a]	18.2[b]	11.25[b]	1.25[a]	2.43[b]	2.91[b]	13.36[a]
WBF 100% (T5)	N/A*	N/A*	N/A*	N/A*	N/A*	N/A*	N/A*
PSE	2.10	0.80	0.15	0.01	0.07	0.001	0.004

Values in the same column with different superscripts (a, b) are significantly different from each other ($p < 0.05$)

PSE pooled standard error

*Mortality in treatment 5 was 100%. Accordingly, no data were available for the studied parameters

Table 4 Differential white blood cells count (in %) for juvenile *Siganus rivulatus* fed with increasing % of waste-based feed (WBF)

Treatment	Neutrophils	Thrombocytes	Lymphocytes	Monocytes
CF 100% (T1)	2.67[a]	77.67[a]	16.67[a]	3.33[a]
WBF 25% (T2)	2.33[a]	79.33[a]	15.00[a]	3.67[a]
WBF 50% (T3)	3.67[a]	81.00[a]	9.67[a]	5.67[a]
WBF 75% (T4)	3.12[a]	82.20[a]	9.30[a]	3.20[a]
WBF 100% (T5)	N/A*	N/A*	N/A*	N/A*
PSE	0.56	2.21	1.66	0.50

Values in the same column with different superscripts (a, b) are significantly different from each other ($p < 0.05$)

PSE pooled standard error

*Mortality in treatment 5 was 100%. Accordingly, no data were available for the studied parameters

Table 5 Moisture, ash content, protein and lipid as percent of dry matter of juvenile *Siganus rivulatus* fed with increasing percentage of waste-based feed (WBF)

Treatment	Moisture	Ash	Protein	Lipid
CF 100% (T1)	66.86[a]	10.17[a]	57.98[a]	34.13[a]
WBF 25% (T2)	65.50[b]	10.05[a]	56.23[a]	36.07[a,b]
WBF 50% (T3)	65.20[b]	10.27[a]	55.46[a]	37.02[a,b]
WBF 75% (T4)	64.76[b]	10.67[a]	50.80[b]	40.42[b]
WBF 100% (T5)	N/A*	N/A*	N/A*	N/A*
PSE	0.30	0.30	1.14	1.41

Values in the same column with different superscripts (a, b) are significantly different from each other ($p < 0.05$)

PSE pooled standard error

*Mortality in treatment 5 was 100%. Accordingly, no data were available for the studied parameters

counts among treatments (Table 4). Eosinophils and basophils were totally absent from all slides.

Food waste can be used to partially replace fish feed in aquaculture. The present work suggests that under controlled experimental conditions possibly up to 73% replacement of commercial fish feed with waste-based feed does not significantly affect survival, growth, hematology and proximate composition of juvenile *S. rivulatus*. However, significant effects on survival were noted with 100% replacement (100% mortality). This is probably because the food waste diet was deficient in essential amino acids, vitamins, or minerals necessary for fish metabolism. The commercial feed must have contained enough of these nutrients to keep the fish alive. Whole-body proximate compositions reported as a proportion of dry weight of fish are summarized in Table 5.

Although significant differences were observed in moisture content, lipid and total protein proportions among treatments, no differences were noted in the ash content. Means of total proteins and lipids for treatment 4 were 50.80 ± 4.09 and $40.42 \pm 3.72\%$, respectively. As total protein offered to the fish decreased and total food lipids increased, the fish started storing adipose tissue at the expense of protein. Consequently, although the fish grew by the same weight, those offered 75% WBF were fattier than those offered 50% or less WBF.

Food wastes include various categories that could provide nutrients and energy for fish. Meat, poultry and fish wastes could be used as protein and lipid sources for fish nutrition, while wastes of fruits and vegetables could provide carbohydrates and fibers (Garcia et al. 2005). A mixture of these wastes appears not to affect digestion capacity of rabbitfish, probably because herbivorous fish tend to utilize plant proteins and because of the enzymatic apparatus in the long digestive system of these species (Smith 1989). Partial replacement of fishmeal-based commercial feeds with WBF did not negatively affect growth and feed conversion of *S. rivulatus* juveniles probably because the fish got their necessities of essential amino acids and fatty acids from the commercial diet and used the waste-based diet for energy and non-essential amino acids and fatty acids.

Usually, fish have specific nutrient and energy requirements for survival and healthy growth and metabolism. According to the NRC (1993), the diet should provide sufficient non-protein energy for survival and maintenance; otherwise, the energy needed will be supplied using proteins at the expense of growth. In addition, fish have optimum dietary protein and lipid requirements. In the present work, both diets had similar gross energy content but differed in the amount of digestible energy which was 14.99 MJ/kg and 17.11 MJ/kg for CF and WBF, respectively. Abou-Daoud et al. (2014) reported that diets containing around 14.2 MJ of digestible energy with sufficient amounts of crude protein provide adequate growth of juvenile marbled rabbitfish when the essential nutrient requirements are met. Accordingly, both CF and WBF diets used in the present study provided enough digestible energy to the experimental fish although the sources of this energy were different. The fact that up to 73.2% of CF could be replaced with WBF without significant effects on survival and growth suggests that nutritional energy is provided by both diets. Additional replacement of low-lipid commercial feed with lipid-rich WBF limited growth probably because the ratio of protein to digestible energy dropped below the 17–26 g/MJ range recommended by NRC (1993). Alternatively, growth could have been reduced by a lack of sufficient essential nutrients or vitamins and minerals. For example, deficiency in dietary lysine can reduce protein deposition and enhance lipogenesis (Brown et al. 2008; Peres and Oliva-Teles 1999;

Phumee et al. 2011), thus limiting growth. As reported by Ghanawi et al. (2011), the increase in lipid content can have an effect on survival, growth, hematological parameters and fish proximate analysis. Although many researchers suggest that fish limit feed intake according to energy content of the diet, Du et al. (2005) and Ayisi et al. (2017) suggest that protein content is more important. This might explain the reduction in fish growth revealed in the present work when CF was replaced by more than 73% with low-protein WBF. Alternatively, fish growth may have been limited by the increase in lipid-to-protein ratio. Ghanawi et al. (2011) established optimal dietary lipid requirements for *S. rivulatus* juveniles as 98 g/kg of fish feed. If the amount of lipid provided exceeds the optimum quantity required, a decrease in growth will be observed (Du et al. 2005) as this increase in lipid content tends to affect the ability of the fish to digest food and absorb nutrients (Luo et al. 2005; Wang et al. 2005). Although break point analysis suggests that fish grow well at 75% WBF dietary replacement, proximate composition of the fish suggests that a 50% WBF replacement is a better value because then fish growth is in protein deposition not fat.

In general, the increase in dietary lipid content of fish is associated with the increased whole-body lipid proportion in various body parts such as the visceral cavity, liver and muscle tissues (López et al. 2006; Song et al. 2009; Wang et al. 2005). HSI was significantly different in the fish of treatment T4 as compared to the other treatments. This may be attributed to the fact that the fish in treatment T4 grew at a lower rate than the fish in the other treatments and not due to the size of the liver. Ghanawi et al. (2011) showed that HSI of *S. rivulatus* was not significantly affected by lipid content in the diet since *S. rivulatus* seem to store lipids in their viscera and muscles and not in their liver. They also observed that fish size had a significant effect on HSI.

Although VSI appeared to be slightly greater in fish of treatment T4, there were no significant differences in VSI among all treatments. Since treatment T4 fish were being offered a lipid intensive regimen, the only explanation for not having a higher VSI is that the fish were consuming less of the diet offered which is very plausible given that the WBF was rich in lipids.

Hematological and biochemical indices are sensitive indicators of the physiological status of fish and are influenced by endogenous and exogenous factors (Wang et al. 2011). These indices include hemoglobin (Hb), hematocrit (Hct) and total plasma proteins (TPP), parameters usually tested for an indirect evaluation of the nutritional status of fish (Hoar et al. 1992; Riche 2007). Low protein content in the WBF compared to the CF could have affected Hct because it was deficient in certain essential amino acids or other nutrients (Lunger et al. 2006). Hemoglobin content tended to decrease as WBF replacement of commercial feed increased. This suggests the possibility of deficiency in some micronutrients such as iron (Clauss et al. 2008). Hemoglobin differences among treatments were not statistically different from each other, which suggests that the experiment was not long enough for the deficiency to start affecting blood pigment. It is possible that for the long-term growth of the fish, a lesser proportion of WBF should be used or may be blood meal from local butcheries added to the diet mix. Total plasma proteins were not affected by the replacement of CF by WBF in *S. rivulatus* juveniles. Finally, there were no differences in the white blood cells profiles among treatments, suggesting that the WBF did not cause intestinal inflammatory responses which are sometimes associated with non-digestible feeds.

Food waste (households or restaurants) is usually characterized by excessive moisture content but requires minimal industrial pre-treatment. Negligible expenses on energy requirement and transportation are needed for local processing of food waste into other useful substances. However, if wastes are to be used as nutritive substances, then protein, lipid and carbohydrate content need to be known in order to understand amounts to be offered to animals. The moisture in the raw ingredients need not be an adverse property. Although the waste in the present experiment was dried, in commercial settings a feed pellet could be made using the wet raw material. However, the ingredients and processing protocols used should provide a form of pasteurization while still maintaining feed integrity at least for animal-derived proteins in order to avoid biological contamination of the aqua feed and harm the aquatic organism (Wood 1995).

Nutrients present in collected food waste would be expected to vary based on the menu and plates offered and season of collection. However, with a relatively consistent menu in restaurants with similar offerings (Lebanese food in the present work), the end product can be assumed to have a relatively consistent composition in terms of proteins (amino acids), lipids, carbohydrates and fibers. Accordingly, variations over a grow-out period of a fish would not be consequential to growth and other production variables.

Aquaculture, similar to all food production industries, has environmental consequences mainly related to fish feed production and use. Production of aqua feed from food waste decreases the environmental impact of using original raw materials. However, incomplete diets tend to cause incomplete digestion with consequent pollution by unused nutrients (Chong 1993). Moreover, shipping material back and forth usually has a high carbon footprint because of increased CO_2 emissions (fuel/energy consumed). A feed mix composed of nutritionally complete feeds to offer essential nutrients and waste-based feed that offer energy compounds and non-essential amino acids to complement the diet would be doubly beneficial. It would reduce the environmental impact of producing commercial feeds from new raw ingredients and would reduce the environmental impact of disposing of food wastes. In areas where large feed manufacturing industries exist, the food waste can be incorporated into the feed manufacture process. In isolated rural settings, commercial feed can be safely and productively complemented with WBF as proven in the present work.

Conclusion

In a world with more than 800 million people suffering from chronic undernourishment (FAO and IFAD 2015), it is imperative that new ways to produce more food sustainably while reducing food waste be explored. Results of the present study suggest that post-consumer food waste can be productively used to substitute for at least 50% of commercial fish feed for growing marine herbivorous fish without apparent detrimental effects. This could induce huge savings on the cost of feed production which translates into less expensive fish on the market. Globally, 332,000 tons of rabbitfish were produced in 2015 (FAO 2017) which corresponds to *circa* 530,000 tons of commercial feed utilized. If 50% of commercial feed is substituted with food waste-based feed without any significant effects on survival, growth rate and physiological conditions, then 265,000 tons of non-sustainable fresh ingredients could be replaced by post-consumer food waste annually for rabbitfish aquaculture alone. Our results need to be confirmed by on-farm long-term studies but are very promising.

The benefits of the present findings are multifaceted, including economic benefits for farmers, increased employment in collection, processing and distribution of waste-based fish feed in addition to a reduction in pollution associated with landfill dumping. As the aquaculture industry continues to grow, a sustainable and environmentally friendly feed such as one based on food waste will become imperative and highly attractive. Furthermore, redirecting food waste away from landfills into production of nutritious protein would increase food security in a vulnerable region while reducing the adverse environmental impact of food waste disposal.

Acknowledgement This project was partially funded by the University Research Board at the American University of Beirut Grant Number URB-103181 and the Lebanese National Council for Scientific Research Grant Number CNRS-LB-103253.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interests.

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