



Export-Driven, Extensive Coastal Aquaculture Can Benefit Nutritionally Vulnerable People

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Export-orientated shrimp and prawn farming in coastal *ghers* has been associated with negative environmental, social, and nutritional impacts. This study challenges these perceptions based on field observations from four communities in South West Bangladesh. Most households observed (>60%) were either directly involved in seafood farming or engaged elsewhere in the seafood value chain. Our study set out to establish how the type and location of aquaculture impacted on access to and consumption of aquatic animals. Additionally, we assessed the effects of both household socioeconomic status and intra-household food allocation on individual diet and nutritional outcomes. We used a blended approach, including a 24-h consumption recall on two occasions, analysis of the proximate composition of aquatic animals and biomarkers from whole blood from a sample of the target population. The diverse polyculture systems generated broad social benefits, where “export-oriented” production actually supplied more food locally than to global markets. Key findings: (1) worse-off households achieved higher productivity of farmed aquatic animals on smaller landholding than better-off households with larger landholdings; (2) vegetable production on *gher* dikes was a significant source of nutrition and income in lower saline gradients; (3) more fish was eaten in lower saline gradients although fish consumption was highly variable within and between households; (4) intra-household allocation of specific foods within diets were similar across communities; (5) recommended nutrient intakes of protein and zinc exceeded daily requirements for adolescent females, but energy, calcium, and iron were below recommended intake levels; (6) n-3 LC-PUFA, expressed as percentage of total fatty acids, in whole blood samples of adolescent females declined with ambient salinity level regardless of household socioeconomic status; (7) analysis of aquatic animals consumed found that mangrove species and tilapia harvested from higher saline *ghers* contained high levels of desirable PUFAs. These findings suggest that export-driven, extensive coastal aquaculture can be nutrition sensitive when co-products are retained for local consumption.

Keywords: nutrition sensitive aquaculture, n-3 fatty acids, polyculture, export and local food, fishery-aquaculture continuum

INTRODUCTION

Aquaculture production focused on supplying export and affluent urban markets has been criticized for diverting nutrients away from the poor and threatening their nutritional security (van Mulekom et al., 2006; Golden et al., 2016). Furthermore, the evidence base for aquaculture supporting nutritional security is poor (Béné et al., 2016). Aquaculture is typically framed as a dichotomy of intensive monocultures producing high-value seafood for the wealthy or low-input, smallholder systems producing food for the poor (Bush et al., 2019). In particular, coastal aquaculture focusing on high-value shrimp production has been criticized for a perceived range of negative social and environmental outcomes (Bailey, 1988). Coastal aquaculture in Bangladesh has now been tagged as maladaptation in terms societal response due to its vulnerability to the negative impacts of climate change through cyclones and sea level rise (Paprocki and Huq, 2018). Its export-oriented focus on high-value shrimp has been implicated in the Southwest coastal zone becoming a (food) “desert in the delta” (Swapan and Gavin, 2011) and that it represents a loss of food sovereignty (Paprocki and Cons, 2014). A major criticism of shrimp farming in Bangladesh is its association with negative impacts on local diets and public health (Rahman et al., 2011a). Nationally, rapid development of fish culture based on a limited range of stocked species has been explicitly linked to poorer livelihood and, specifically, nutritional outcomes (Roos et al., 2003b).

A better understanding of the mechanisms for aquaculture being “pro-poor” requires analysis of both direct and indirect pathways and the role of production and consumption to be understood (Toufique and Belton, 2014). Both community level and intra-household perspectives are required for a full understanding of the development impacts of aquaculture (Béné et al., 2016), both on vulnerable individuals and in terms of broader livelihoods (Chambers and Conway, 1992). Livelihoods frameworks have been found useful to capture the complexity and heterogeneity of rural coastal contexts elsewhere in Asia to inform policy (Pham et al., 2020).

Major progress has been made in addressing basic food security in Bangladesh and the severity of several micronutrient deficiencies has been reduced in the last two decades, but “hidden burdens” remain a key challenge for vulnerable groups. Preschool children remain susceptible to anemia and vitamin A and D and zinc deficiency, whilst more than half of non-pregnant, non-lactating women are zinc deficient, more than 40% lack iodine rich food. A significant proportion of the population (>20%) are anemic and dietary intake for vitamins A, D, and B12 is also low (Ahmed et al., 2012). Anthropometric data obtained in pre-school children in Bangladesh indicated that more than a third (36%) were stunted and underweight and about 14% suffered from wasting (Global Nutrition Report, 2020). Investment in ensuring adequate nutrition during the critical 1,000 days, pregnancy and the first 2 years of life, has been identified as critical for intergenerational welfare (Martorell, 2017). Bangladesh has high levels of pregnancy among female adolescents, and almost half have given birth by 18 (Blum et al., 2017). This carries particular risks (NIPORT, 2013) and makes

adolescent females a highly vulnerable group to welfare-related issues. Increased research into the nutrition of young people (Akseer et al., 2017) and micronutrient deficiencies in female adolescents in particular are timely.

Strategies to improve nutrition and health outcomes of such vulnerable groups need to be culturally attuned and based on high accessibility and affordability (Jennings et al., 2016). Studies suggest that under-consumption of micronutrient dense food is common in both “worse-off” and “better-off” contexts (Keats et al., 2018; Mitsopoulou et al., 2020) which has been linked, at least partially, to fast food substitution (Li et al., 2020). The limited studies of adolescents in rural South Asia suggest that dietary patterns are strongly linked to socioeconomic status and gender in Bangladesh (Blum et al., 2017; Thorne-Lyman et al., 2020) and Eastern India (Unisa et al., 2020). The role of seafood as a source of micronutrients in the diets of vulnerable populations that are highly dependent on aquatic foods is critical (Coulthard et al., 2011).

The contribution of fish (fish is used interchangeably here for aquatic animals and seafood) to food and nutrition security is important in terms of contributing high-quality animal protein as well as important micronutrients and lipids. Inclusion of animal-source foods in diets improves growth, micronutrient status, and cognitive performance in children in low-income countries (Dror and Allen, 2011). The specific nutritional contribution of fish may be particularly important in populations with very limited general access to dairy and terrestrial livestock and where there is ready access to a rich aquatic diversity (Little et al., 2018). Both conditions exist in Bangladesh. Fish and seafood are well-documented for their contribution of a wide range of essential micronutrients, vitamins, and n-3 long-chain polyunsaturated fatty acids (n-3 LC-PUFA) (Karapanagiotidis et al., 2006).

Export-driven shrimp and prawn farming in Bangladesh has expanded 10-fold, from an estimated 20,000 hectares in the early 1980's to more than 275,000 hectares (BFFEA, 2015). The rapid growth of shrimp and prawn farming is positively correlated with national economic growth (Ahmed et al., 2010; Ito, 2010). In parallel, rapid development, and commodification of farmed, mainly freshwater fish serving domestic markets has occurred (Hernandez et al., 2017). The replacement of small indigenous species (SIS) in peoples' diets by such conventional aquaculture species has been linked with poorer nutritional outcomes (Roos et al., 2003a). Due to this shift in fish species diversity in diets, iron and calcium intake through fish has dropped in spite of increased overall fish consumption (Bogard et al., 2017a).

However, the causal pathways to impacts on human health are often lacking as is a contextualized understanding of the nutritional role of fish in broader diets and resultant impacts on health (de Roos et al., 2019). Also, documentation of the distribution of fish within the household is often neglected, though important. Male head of households farming fish in Bangladesh were favored in the distribution of a fish meal among family members; females received on average 63% of the portion size of the household head, while other males in the household received portions amounting 84% of the head (Roos et al., 2003a). The inequities of intrahousehold food distribution disfavoring females was

identified as a general pattern of concern in Bangladesh (D'Souza and Tandon, 2019).

Assessing health status, and how this relates to nutritional intake, remains a challenge. The use of biomarkers of intake, which for some nutrients are also recognized as biomarkers of efficacy, are starting to provide more powerful insights (de Roos et al., 2019). For example, n-3 LC-PUFA levels in blood are increasingly used as a health biomarker. In a well-designed study (Harris et al., 2020), the proportion of n-3 LC-PUFA (EPA+DHA) to total LC-PUFA, known as the Omega-3 Index, was linked to greater longevity and reduced cardiovascular disease risk. LC-PUFA are produced naturally by aquatic, predominantly marine micro algae and become concentrated through the food chain, particularly in some fish and other marine animals. As their importance to human health and that of farmed fish has become clearer, a supply gap has emerged as traditional sources of n-3 LC-PUFA (fish oils) are limited (Tocher et al., 2019). Distribution of these key products in the heterogeneous aquatic farming systems and species of Southwest (SW) Bangladesh have been little studied to date. Linking agroecosystem characteristics to the nutritional quality of food produced and resulting nutritional and health benefits among vulnerable people was a key objective of the study.

This field observational study aims to assess the importance of aquaculture in communities located across a salinity gradient in SW Bangladesh and, specifically, to determine its nutritional and health impacts on adolescent females. Production of, and access to, stocked and unstocked aquatic animals was hypothesized to be an important factor in the nutrient profiles of local diets. This paper, as a first step, describes the diversity of coastal floodplain aquaculture systems, food availability, and broader livelihoods (Chambers and Conway, 1992). We then assess differences in food consumption patterns in communities located along a saline gradient, and characterize intra-household food allocation of farmed aquatic animals and associations with the health status of vulnerable individuals.

This paper contributes a contextualized understanding of how land used for a commercial export-orientated aquaculture can contribute toward diversified food production and nutritional security locally.

METHODS

Communities characterizing aquaculture production in the Greater Khulna Area across four different salinity levels High Saline (HS), Medium Saline (MS), Low Saline (LS), and Freshwater (FW) were selected purposely based on the previous cluster analysis the EC FP7 funded Sustaining Ethical Aquaculture Trade (SEAT) (Murray et al., 2013). Qualitative and quantitative methods were coupled to explore household socioeconomic status, food consumption patterns and the health and nutritional outcomes of adolescent females. Key informant (KI) interviews led to identification of four indicative communities, in which Hindu households were a significant proportion (>20%). Participatory research activities (transect walks, village mapping, household socioeconomic ranking were

conducted with KIs). A detailed understanding of the overall farming systems in each community was based on in depth interviews with 40 aquaculture producer households randomly sampled from each community.

A census ($n = 1,082$) of all households led to identification of 240 households with at least a single adolescent female from the same frame, again with randomized-stratified sampling based on socioeconomic categories for “intra-household” analysis. This resulted in sampling of 60 households per community consisting of 30 “better-off” and 30 “worse-off” households, following socioeconomic ranking of households by community leaders. Further analysis was conducted on livelihood options, intra-household food distribution and aquatic farming assets. Both the rich and medium household categories were combined into “better-off” and poor and ultra-poor into “worse-off” socioeconomic groups. A 24-h food recall method, food frequency questionnaire, food photography, and measuring cup sets were used to estimate food consumption for individual members from the sampled households. Anthropometric measures [stunting, wasting, Body Mass Index (BMI), Mid-Upper Arm Circumference (MUAC)] and levels of fatty acids [calculated n-3 LC-PUFA in RBC and n3:n6 ratio (n-3 LC-PUFA/n-6 LC-PUFA) in whole blood cell] were used to assess nutritional outcomes of adolescent female ($n = 200$ females). Samples of shrimp/prawn and fish polyculture species (57 species and 9 by-products, $n = 672$) were collected randomly from farmers' production systems across the major agroecologies (HS, MS, LS, and FW) and intensification level (extensive, semi-intensive, intensive). Macro and micronutrient content of the edible fraction of each sample were analyzed and formed the basis to assess distribution at the intra-household level.

Reference values for Body Mass Index (BMI), Mid-Upper Arm Circumference (MUAC) (NIH, 2016; WebMd, 2016), total n-3 LC-PUFA content in blood, ratio of n-3 LC-PUFA to total LC-PUFA (Lands, 2003; Harris, 2007), and recommendent nutrition intake (RNI) essential micronutrients, protein, and energy were obtained from standard sources (Islam et al., 2010; INFS, 2013; UNICEF, 2013). All analyzed data, graphical presentation of data have been customized from the statistical package program R (R Core Team, 2016). Detailed methods are supplied in the **Supplementary File 1**.

RESULTS

Coastal Floodplain Aquaculture Systems

Saline-impacted, coastal Bangladesh is an area of particular vulnerability. The livelihoods of an estimated 38.5 million people based on terrestrial farming and, increasingly, aquaculture are affected by salinization, which has been linked to climate change (Kabir et al., 2016). The pattern of farming systems are characterized both seasonally and spatially along a transect stretching from the coastline to more than 150 km inland in Greater Khulna and is complicated by polder construction and related water logging stretching back to the 1960's (Foxon, 2005). Low productivity of the single rice crop stimulated adaptation of rice fields through trenching and bund raising to shallow impoundments, locally known as *ghers* (Milstein et al., 2005)

which, depending on salinity regime, may continue to be used for seasonal rice cropping. The area remains one of the most extensive systems of indigenous shrimp farming in the world (Tenison-Collins, 2016), supporting an estimated 80% of the national production of black tiger shrimp (shrimp; *Penaeus monodon*). This major concentration of coastal aquaculture is close to the relatively well-conserved Sundarbans mangrove forest that has largely resisted conversion to aquaculture (Hamilton, 2013). Traditionally, shrimp were raised together with finfish in a polyculture that complemented the seasonal social and ecological rhythm of rural life in Bangladesh (Pokrant, 2014). The majority of shrimp production remains low-input, and largely based on fertilization supplementing natural productivity through exchange of water. In contrast, giant freshwater prawn (prawn; *Macrobrachium rosenbergii*), the target export crop in freshwater systems further inland, are farmed in semi-intensive *ghers*, integrated with rice production, and reliant mainly on feed (Jahan et al., 2015).

Characteristics of aquaculture and broader farming systems are summarized in **Table 1**. In all communities, fish yields tended to be low (around 1 MT/ha), and produced for both export and local markets. Export crops, mainly shrimp, only dominated in the high saline (HS) gradient, approaching 50% of the total harvest. In other locations, export products ranged from 20 to 40% of the total harvest. Diverse aquaculture systems characterized the communities across the saline transect and aquatic animals are disaggregated (**Figure 1**) as crustaceans (i.e., shrimp and prawns), marine fish, freshwater fish and

tilapias. There were significant differences in associated terrestrial cropping; production of rice and vegetables were inversely related to salinity levels.

In terms of overall harvested yield, shrimp dominated in HS, and prawn in LS and FW systems. Freshwater fish were harvested at all sites but mainly in LS and FW, where they contributed 78 and 58% of total yield, respectively (**Figure 1**). In contrast, mangrove fish were most important in HS (20% of total yield) and MS (16%), reflecting closer proximity to the Sundarbans mangrove forest. Tilapias were present across the saline transect, except for the FW environment; over 90% of *ghers* in higher saline gradients (HS, MS) had tilapia comprising 13 and 18% of total production volume in HS and MS areas, respectively (**Figure 1**). Household socioeconomic level (Morales, 2007) was associated with the types of fish and harvested yield. Across the four locations “worse-off” households on significantly smaller landholdings had higher fish productivity ($P < 0.05$) than “better-off” households on their larger landholdings (**Figure 1**). Apart from fish, vegetables, and rice were produced in the lower saline gradients (LS, FW). Most of the vegetables produced were destined for market sale whereas rice production was subsistence-orientated.

Coastal Zone Livelihoods

The majority of households (>60%) in the four communities had access (owned/leased-in) to an aquatic farming system (**Table 2**). The specific topography in the HS community, characterized by relatively high elevation, explains the lower participation in

TABLE 1 | Key characteristics of aquaculture-agriculture system by community.

Item	Variables	Area			
		High saline (HS)	Medium saline (MS)	Low saline (LS)	Freshwater (FW)
Number of farms		40	40	40	40
Location	Distance from mangrove (km)	<2	35	40	50
	Distance from Khulna town (km/hrs:mins)	130/3.40	85/2.20	25/1	66/2
Land holding	Gini co-efficient	0.54	0.45	0.45	0.54
Income	Gini co-efficient	0.28	0.26	0.29	0.27
Inputs	Water salinity (ppt)	>10	>5<10	<5	<0.5
	Juveniles* (stocked \times 1,000; no. mean \pm SD)	87.6 \pm 29.9	61.6 \pm 26.2	36.1 \pm 25.7	16.6 \pm 8.5
	Fertilizer for aquatic animal production (mt ha ⁻¹)	0.59 \pm 0.6	0.42 \pm 0.28	0.28 \pm 0.22	0.07 \pm 0.06
	Feed (mt ha ⁻¹)	0.077 \pm 0.04	0.156 \pm 0.17	0.75 \pm 0.69	1.33 \pm 0.58
Cost (rental, labor etc.)	Operational cost (US\$ ha ⁻¹ yr ⁻¹)	703	610	1,230	1,948
Yield (t ha ⁻¹ yr ⁻¹)	Aquatic animal yield	0.91 \pm 0.39	0.67 \pm 0.26	1.14 \pm 0.49	0.97 \pm 0.49
	Rice	–	–	1.5	2.5
	Vegetable	–	–	2.7 \pm 3.2	6.5 \pm 4.4
Benefit	Gross margin for all crops (US\$ ha ⁻¹ yr ⁻¹)	231.6	133.9	222.4	177.5
Market orientation of fish	Dedicated to export market and/or crustaceans to total fish volume (mt harvest) (%)	47.5	37.3	19.9	20.7

*Juveniles = for crustaceans PL (post-larvae) and for fin fish fry and fingerlings.

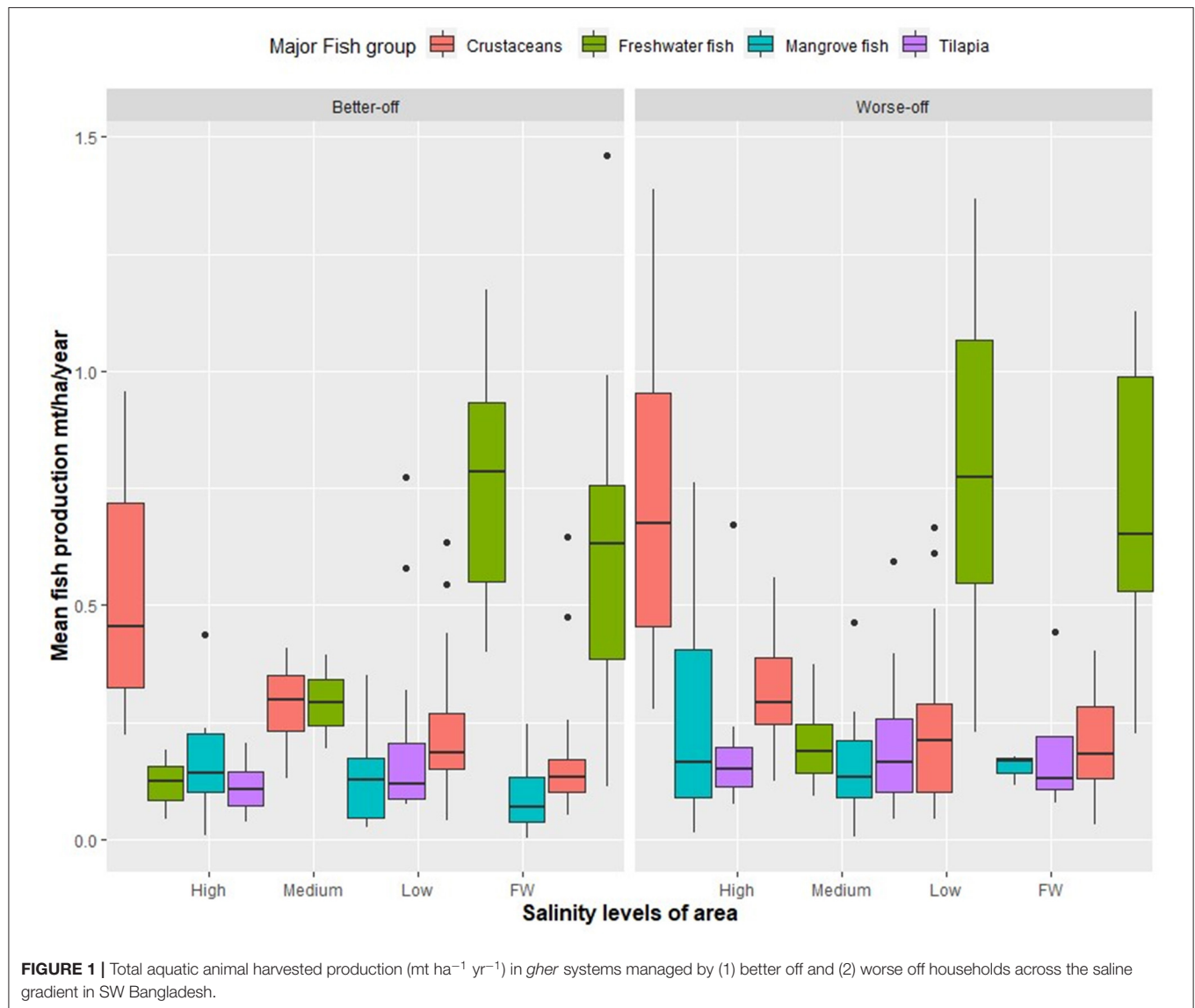


TABLE 2 | Share of households (%) with access to *gher* by salinity zone and socioeconomic grouping in south-west Bangladesh.

Household well-being	Salinity level (no. of HH)				Mean total land holding in ha (min-max)*
	High saline (273)	Medium saline (206)	Low saline (298)	Freshwater (305)	
Rich	100% (22)	96% (25)	87.2% (39)	90% (41)	2.4 (1.05–3.7)
Medium	85.7% (91)	100% (47)	69.7% (114)	91.4% (70)	1.14 (0.7–1.4)
Poor	46% (137)	81.4% (86)	56.3% (119)	77% (122)	0.7 (0.4–1.1)
Ultra-poor	8.7% (23)	66.7% (48)	38.5% (26)	54.2% (72)	0.4 (0.16–0.7)
Geographical information	Arapangasia, Shaymnagar, Satkhira	Jaduardanga, Ashashuni, Satkhira, salinity	Shuvna, Dumuria, Khulna	Chor-Borobararia, Chitalmari, Bagerhat	
Water salinity	10 ppt	>5<10 ppt	<5>0.5 ppt	<0.5 ppt	

n, number of households. Total number of households assessed = 1,082.

*Land area based on post-hoc analysis (mean with max and min values) of land area of households. Both rich and medium households formed better-off segment whereas poor and ultra-poor households formed worse-off.

fish production for which their land is less suitable. Ownership of, or leased-in access to, *ghers* was affected by household socioeconomic status. While “better-off” households had more access to *ghers*, even “worse-off” households had significant participation in aquaculture through leasing arrangements. The income Gini values (0.26–0.29) were also indicative to this lower disparity, compared to land holding Gini values (Table 1).

Agro-ecologies appeared to influence the types of household likely to be involved directly in aquaculture and mean area of land holding (Table 2). Limited off-farm livelihood opportunities in MS and FW areas pushed more ultra-low socioeconomic households into aquaculture; gross margins from aquaculture were also significantly lower in these two communities. This is mainly explained by limited off-farm livelihood options (Supplementary Table 1) related to their greater geographical isolation, and traveling times to mangroves (MS) and urban areas (FW) compared to HS and LS communities, respectively (Table 1).

Food Consumption Levels Across the Saline Gradient

The average levels of consumption of different food group's intra-household food allocation patterns were similar across the salinity gradient; however, overall fish consumption was higher in lower saline compared to higher saline locations (Supplementary Table 2).

Overall household consumption of some non-fish dietary components varied with position in the saline transect, e.g., less meat was eaten in HS, and more milk and eggs were consumed in MS than other locations. Daily intake of meat and fruit consumption was similar, although the food frequency study indicated the better-off tended to eat these nutritious food items more frequently than “worse-off” households (Supplementary Figure 1). There were no significant differences in consumption of any food group between household members, household socioeconomic status or location, except for cereals, where “better-off” households tended to consume significantly (P

< 0.05) more cereals (1,670 g/capita/day) than “worse-off” (1,545 g/capita/day) (Table 3).

A higher proportion of individuals within households ($> 90\%$) consumed fish than any other food group except cereals and vegetables. In contrast < 13.5 , 13.0, and 18.0% consumed any meat, milk and eggs, respectively, during the two 24 h dietary recall periods (Table 3). Within households, fish consumption was highest for adult males; the mean daily fish consumption of adolescent and adult females was 20% lower ($P < 0.05$) than adult and adolescent males. Adolescent females consumed less fish than other household members (Table 3).

Levels of fish consumption were highly variable within and between households and were impacted by both geography and household socioeconomic status (Supplementary Table 2). Households in the LS consumed significantly less fish than in other areas; intake in the FW, MS, and HS areas was similar (Supplementary Table 2). Better-off households consumed over 20% more fish than worse-off households (122 vs. 100 g/day, $P < 0.05$; Supplementary Table 2).

Contribution of Fish Consumption to Nutrient Intake

Estimated macro and micro-nutrient consumption suggested that consumed total energy levels for adolescents were below the daily recommended nutrient intake (RNI) (NIH, 2016; WebMd, 2016) while those for adults slightly exceeded them (required energy for male 2,900 Kcal; female 2,300 Kcal). Overall individual protein intake was found to be well above the RNI for all household members with a major (about 25%) proportion of total protein derived from fish. Protein consumption by adolescent female was found to be 2–3 times higher (data not shown) than the RNI level (NIH, 2016; WebMd, 2016).

Estimated micronutrient intake compared to RNIs (FAO, 2001; NIH, 2016; WebMd, 2016) were variable (Table 4). Estimated zinc consumption of all household members was 20–50% higher than the RNI (Table 4). In contrast, calcium consumption was particularly low for all household members,

TABLE 3 | Summary of mean (\pm SD) daily intake of each food group by individual household members in four communities located across a saline gradient in SW Bangladesh based on two 24 h recall periods [the number in parenthesis is frequency of the individual that consumed the food item].

Food groups	Male adult ($n = 219$)	Female adult ($n = 233$)	Adolescent male ($n = 130$)	Adolescent female ($n = 289$)
Cereals	2,028 \pm 624 (219)	1,684 \pm 519 (233)	1,662 \pm 673 (130)	1,168 \pm 425 (289)
Fish	116 \pm 91 (202)	98 \pm 68 (219)	108 \pm 89 (117)	94 \pm 70 (268)
Vegetables	428 \pm 2 (218)	380 \pm 184 (230)	360 \pm 305 (130)	321 \pm 173 (288)
Meat	15 \pm 39 (37)	9 \pm 25 (36)	16 \pm 39 (30)	9 \pm 29 (39)
Pulses (ml)	92 \pm 148 (89)	75 \pm 119 (97)	67 \pm 106 (52)	58 \pm 102 (109)
Milk (ml)	22 \pm 64 (36)	19 \pm 49 (40)	17 \pm 47 (17)	20 \pm 48 (51)
Eggs	9 \pm 21 (53)	7 \pm 16 (54)	9 \pm 17 (36)	8 \pm 18 (71)
Fruits	6 \pm 25 (28)	7 \pm 21 (34)	10 \pm 25 (22)	8 \pm 21 (55)
Beverage (ml)	18 \pm 35 (63)	1 \pm 9 (3)	3 \pm 17 (10)	0.8 \pm 8 (3)
Others*	3 \pm 12 (24)	2 \pm 9 (19)	3 \pm 9 (15)	3 \pm 14 (28)

Unit in g unless mentioned in parenthesis of first column.

*Others is a food group comprising ice-cream, chocolate, etc. In each site 60 households were chosen based on presence of at least one unmarried adolescent female. No significant differences found between locations and socio-economic groups except for cereals.

TABLE 4 | Results showing factors affecting mean micronutrients consumption of household members in relation to the average reference value in the aquatic farming system in SW Bangladesh.

Minerals	Factor	Group	Mean residual	SD	% above (+) or below (–) the threshold level	Significance
Zinc	Salinity	High	3.6	5.1	36.0	ab
		Medium	3.5	5.9	35.6	b
		Low	2.3	4.7	23.0	ab
		Freshwater	3.9	5.8	39.0	a
	Socio-economic status	Better-off	3.9	5.4	39.4	a
		Worse-off	2.8	5.4	27.8	b
	Relation	Adult male	4.5	6.0	45.5	a
		Adult female	4.9	5.3	49.0	a
		Adolescent male	2.1	5.2	20.6	b
		Adolescent female	1.8	4.5	18.5	b
Calcium	Salinity	High	–586.2	328.7	–53.3	b
		Medium	–607.3	313.1	–55.2	bc
		Low	–707.5	250.6	–64.3	c
		Freshwater	–84.8	796.5	–7.71	a
	Socio-economic status	Better-off	–446.9	549.9	–40.6	a
		Worse-off	–533.7	492.7	–48.5	b
	Relation	Adult male	–340.4	602.9	–30.9	a
		Adult female	–515.9	475.4	–46.9	bc
		Adolescent male	–417.5	564.8	–37.9	ab
		Adolescent female	–609.4	445.6	–55.4	c
Iron	Salinity	High	4.06	10.4	33.8	a
		Medium	2.75	9.5	22.9	a
		Low	2.01	9.5	16.7	a
		Freshwater	4.49	10.3	37.4	a
	Socio-economic status	Better-off	4.3	10.1	36.4	a
		Worse-off	2.3	9.8	18.8	b
	Relation	Adult male	10.1	9.9	84.0	a
		Adult female	1.4	8.8	11.9	c
		Adolescent male	7.3	8.6	60.9	b
		Adolescent female	–1.9	7.8	–15.8	d

Different letters (last column) in rows under each factor row indicated significant differences ($P < 0.05$).

irrespective of sex and position, with intakes 30–55% below the RNI. Calcium intake was much lower among adolescent females compared to other household members (Table 4). The iron intake of males was 60–80% more than required and adult females consumed levels 10% above RNI but adolescent females were 15% lower compared to the RNI (Table 4).

The nutrient content of species consumed varied greatly. The level of n-3 LC-PUFA (EPA+DHA in mg/100g^{–1}) varied greatly across different species produced in *ghers* across the salinity gradient. Mangrove fish, such as mullet that mainly enter the *ghers* with tidal exchange, had relatively high n-3 LC-PUFA levels. The main edible fraction of farmed crustaceans had low levels of n-3 LC-PUFA, while tilapia had intermediate levels. Non-stocked species from freshwater areas had higher proportions of total lipids (on a mg per 100 g basis), and specifically n-3 LC-PUFA when compared to hatchery-derived larger freshwater fish, and different crustacean species (Figure 2). However, by-products such as the claws, heads, and specifically brains, of the giant

prawn (*Macrobrachium rosenbergii*) were major sources of fatty acids and essential minerals. The energy content of samples from the current study were comparable with previously published data (INFS, 2013; Bogard et al., 2015).

The specific culture system and agroecology also impacted the nutritional status of aquatic animals produced. A decline in n-3 LC-PUFA content was correlated with ambient salinity level for several key euryhaline species (Figure 2). Of particular note was the trend for tilapias where peak levels of n-3 LC-PUFA were found in fish raised in the MS environment. In contrast, n-3 LC-PUFA (EPA+DHA in mg/100 g) levels in two species of shrimp *Penaeus monodon* and *Metapenaeus monoceros* were much lower across salinity levels (Figure 2).

The availability of high-quality nutritious fish does not necessarily translate to its accessibility and consumption by the most vulnerable groups. Adolescent females had both the lowest levels of fish and overall total food consumption and were identified as the most at-risk group for malnutrition, as evidenced biomarker outcomes (Figure 3).

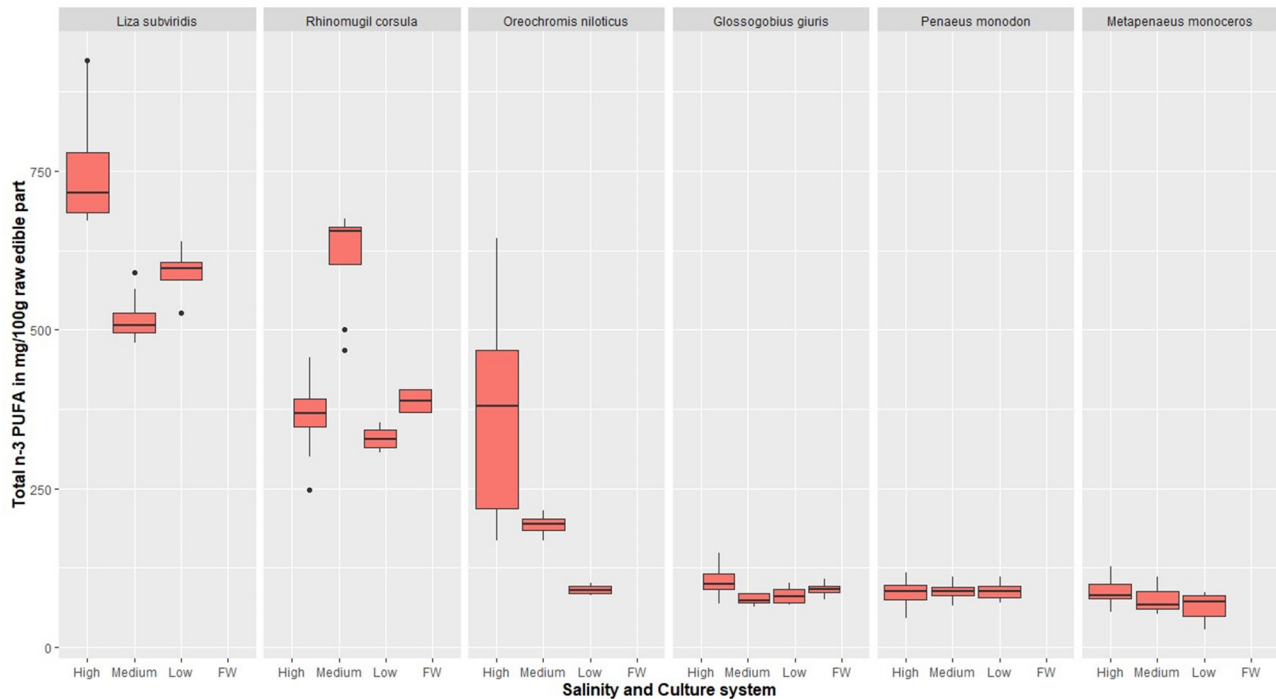


FIGURE 2 | Levels of total n-3 LC-PUFA (mg/100 g raw edible part, mena values; error bars show SD) measured in six fish species found across the range of culture systems and salinity regimes in SW Bangladesh.

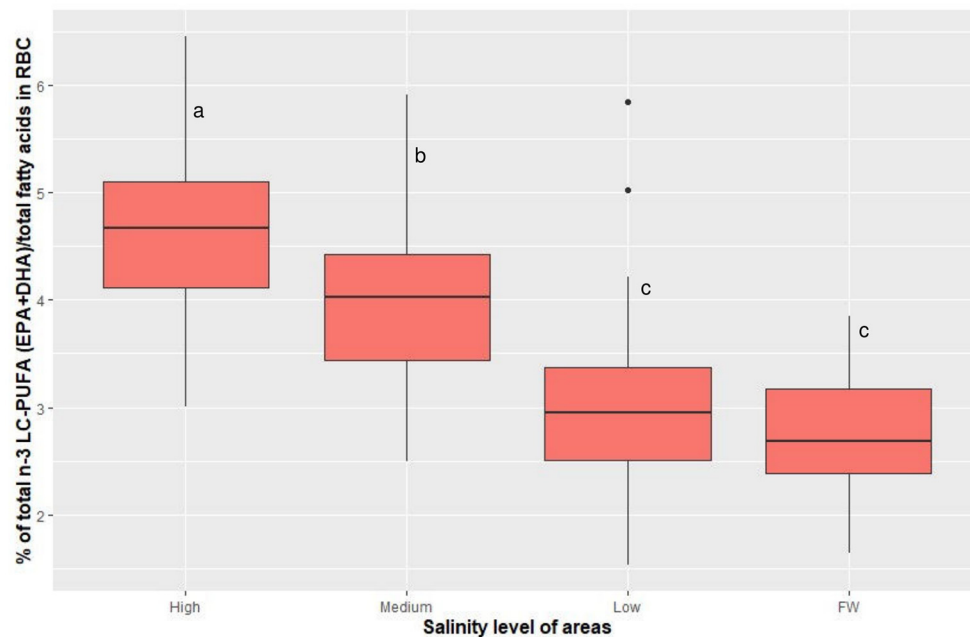


FIGURE 3 | Total n-3 LC-PUFA (EPA+DHA) as a percentage of total fatty acids (w/w) in RBC of adolescent females (10–19 years) across aquatic farming systems located across a saline gradient in SW Bangladesh [for in-depth household level study 60 households from each site with equal number from each social well-being group were considered, however for bloodspot collection we took 50 households from each site; different lettering above each whisker indicate significant differences ($P < 0.05$)].

Indicators of Adolescent Female Health

The comparison of n-3 LC-PUFA levels in red blood cells (where blood was taken whole and then transformed into RBC) of adolescent females living across the salinity gradient revealed a clear relationship (**Figure 3**). However, there was no relationship between n-3 LC-PUFA and household socioeconomic status.

Adolescent females from the HS and MS areas had significantly higher ($p < 0.05$) total n-3 LC-PUFA levels than those located in LS and FW areas (**Figure 3**). No significant differences in n-3 LC-PUFA index ($P < 0.05$) were found between adolescent females from the LS and FW sites. Higher salinity sites were significantly ($P < 0.05$) correlated with higher n-3 LC-PUFA outcomes. The average Omega-3 index was more than 4% in HS declining across the gradients to a low of 2.77% in FW (**Figure 3**). Location in the saline gradient and socioeconomic status did not impact on either body mass index (BMI) values that ranged from 17.48 to 20.8 (**Supplementary Figure 2**) or mid upper arm circumference (MUAC) values, which ranged from 22.1 to 24.11 cm (**Supplementary Figure 3**).

DISCUSSION

This study revealed strong associations between the characteristics of aquaculture and key livelihood impacts of households in the four coastal communities located across a surface water salinity gradient in SW Bangladesh. Aquaculture is practiced by the majority of households in these communities as polycultures, based on both stocked and unstocked species (Faruque et al., 2016), and has broader spillover benefits to the community as a whole through employment and nutrition. Typically characterized as export-focused, much of the production was found to contribute to local consumption. From 45% (HS) to 80% (FW) of the harvested yield was consumed locally, with the balance (mainly shrimp and prawns) entering the processing sector.

While a high level of inequality of access to aquaculture in HS communities adjacent to the Sundarbans area has previously been reported (Abdullah et al., 2017), our study suggests that this characterization was not representative across the saline zone. Our results indicate that apart from the most saline gradients, a significant proportion of “worse-off” households accessed both the means to, and benefits of, aquaculture production through ownership or leasing arrangements of land. Engagement of worse-off households in aquaculture increased household fish consumption (AFSPAN, 2015), although livelihood opportunities in addition to aquaculture, typically natural resource-based (HS) or urban-driven (LS), were still critical to ultra-poor households. Such pluriactivity was focused on exploitation of mangrove resources (fishing, etc.) in HS areas and around urban employment opportunities in LS areas (**Supplementary Table 1**). Greater disparities between rich and poor household incomes were observed in shrimp-prawn farming areas in Bangladesh (Environmental Justice Foundation, 2003; Ito, 2010; AFSPAN, 2015) than in the current study, which indicated a lower income disparity across seafood farming communities. The income Gini value (0.37) of all communities

was within the range calculated for 62 countries (Carter, 2000). Furthermore, there was no correlation between area of land farmed and income levels, supporting the proposition that poverty has become increasingly detached from access to land and even from farming in much of Asia (Rigg, 2006).

Estimated net financial benefits of aquaculture systems across the saline gradient ranged from 134 to 230 USD ha⁻¹ yr⁻¹ (**Table 1**), which is within the range of average return reported in other studies (70–840) (Gammage et al., 2006; USAID, 2006; Abdullah et al., 2017). In the current study, productivity of “worse-off” households farming smaller *ghers* was higher than the “better-off” achieved in larger systems a common phenomenon in food production as a whole (Ramankutty et al., 2018). Coastal shrimp production within mangrove ecosystems have important roles in generating employment for the poor in both Central Vietnam (van Hue and Scott, 2008) and in East Kalimantan, Indonesia (Bosma et al., 2012). Adverse effects of shrimp farming on rice and vegetable production were revealed in a time series study in Bangladesh (Rahman et al., 2011b); however, in LS and FW communities, dyke vegetable and rice production were important parts of farmer livelihoods, a practice which has seen recent rapid expansion, especially by “worse-off” households (Howson, 2014). Pond-dyke farming elsewhere in the country benefits both “better-off” and “worse-off” *gher* owners in rural and peri-urban settings through both cash sales and subsistence consumption (Karim et al., 2011).

Shrimp farming has been framed as an activity that disregards local people's needs (Paprocki and Huq, 2018), and was propelled initially through land grabs by wealthy outsiders, exacerbating disparities (Adnan, 2013). Earlier reports (Swapan and Gavin, 2011) of external investors gaining monetary benefits at the expense of local people were not observed in the current study, suggesting these might be more exceptional than normative outcomes. Indeed, Gini coefficients, high levels of engagement in production and similarity of consumption and health outcomes across social groups suggested that aquaculture was having broader societal benefits.

A reduction in biodiversity through salinization exacerbated by shrimp farming leading to “worse-off” dietary outcomes has been a key criticism of shrimp farming in Bangladesh (Rahman et al., 2011a). The “semi-saline” zone (Guimaraes, 1989) is subject to great dynamic salinity fluctuations across seasons, with individual locations being subject to both increases and declines in salinity over time related to saline intrusion and sedimentation, respectively (Faruque et al., 2016). “Industrial shrimp” systems have been characterized as part of a “blue future” with no rice, livestock, vegetables or freshwater fish, and limiting opportunities for self-provisioning of food (Paprocki and Cons, 2014). A key concern is that intensification of aquaculture systems could reduce access to affordable low-value finfish (Little et al., 2018). Our analysis points to these HS floodplain systems being very low-input, nutrient sinks, indeed the opposite of “industrial” food production, and an important source of highly nutritious local food.

Ongoing reliance on the Sundarbans by “worse-off” households in the HS community remained high in contrast to a previous study (Abdullah et al., 2017), that found dependence

on collection of natural resources by the poorest in this area improved resilience to environmental shocks (such as Cyclone Aila) compared to those engaged in aquaculture (Abdullah et al., 2017). Mangrove-derived fish in all HS and MS *ghers* comprised a significant proportion of total yield, demonstrating the importance of the Sundarbans as a source of biodiverse, self-recruiting species. The importance of porous boundaries and close interaction with natural stocks to maintain productivity and biodiversity has been demonstrated as a common characteristic of freshwater systems throughout Asia (Amilhat et al., 2009). It also points to the strong interrelationship between biodiversity and nutritional outcomes of localized, landscape food systems.

The more obvious agricultural diversity of LS and FW communities has been associated with enhanced food and nutrition security (Faruque et al., 2016) but both consumption patterns and health outcome data in the current study contradicted these conclusions. Although the diversity of local terrestrial cropping systems and intensity (Faruque et al., 2016) were lower in HS and MS gradients, consumption levels of vegetables, fruit and milk were constant across saline zones. This contrasts with earlier observations (Rahman et al., 2011b) of a decline in their consumption following the adoption of shrimp farming. Markets may now be increasing access to all foods due to improvements in market linkages and greater market inclusion (Belton, 2016; Faruque et al., 2016).

Overall, fish consumption was highest at the lower salinity sites, but there were not major differences across the saline gradient. Worse-off households consumed 60–80% of the levels reported by richer households in the same community, except for MS areas where “worse-off” males consumed 20% more fish than the “better-off”; females from “better-off” and “worse-off” households consumed similar amounts. In contrast, a nationwide study reported that “better-off” households, representative of rural Bangladesh in general, tended to consume twice as much fish as worse-off households (average 60 g/person/day) though much lower aggregate levels of total fish consumption overall. Also, dried fish, a concentrated nutrient source, was a significant proportion of total fish consumption nationally, and high levels (80%) of fish were purchased from the market. The current study found relatively high levels of fresh fish consumed in the producer communities studied and a lack of dried fish consumption, suggesting that retention of fresh fish for local use was prioritized.

This work confirmed that Bangladesh females, especially in “worse-off” socioeconomic groups, tended to consume less fresh fish than men (Bogard et al., 2017b). The current study demonstrated significantly lower consumption of cereals, fish, vegetables, and pulses by female adolescents compared to other household members irrespective of socioeconomic status or agroecology. Our study suggests that very low levels of rice consumption by adolescents might restrict energy intake below the RNI; another study found that 25% of adolescent females (and boys) had inadequate energy but, as in the current study, dietary protein was adequate (Leroy et al., 2018). These results contradict other studies that have found animal protein intake to be extremely low in Bangladesh (Ahmed et al., 1998; Khan and Ahmed, 2005; NIPORT, 2013). The high level of dietary

protein consumption in the current study may also have reflected the timing i.e., during the peak dry-season harvesting season, when mobility and fish consumption is typically higher (Morales, 2007). The importance of disaggregating consumption by both gender and age is now more widely accepted, but the distinctive and crucial adolescent phase has often been missed (Haberland et al., 2018). The necessity for understanding the nutritional vulnerability of adolescent females in Bangladesh is further underlined by the enduring high rate of pregnancy in this group and the poorer outcomes for themselves and their children than adults (Nguyen et al., 2018). Recent research has confirmed the high burden of undernutrition in adolescent females in early pregnancy (Mridha et al., 2018).

A dietary pattern approach to assessing diets of adolescents in Northwest Bangladesh found fish to be by far the most important animal food source consumed but identified consistent and important differences in intake and dietary diversity among socioeconomic groups (Thorne-Lyman et al., 2020). Adolescents in the poorest households had the least diverse diets, but access to a fish pond was much lower in this part of Bangladesh (around 25%) than in any of the communities in the current study that were sampled from a known concentration of commercial aquaculture. Affordability was found to be the major factor in determining adolescent's access to nutritious food. The importance of fish in rice-based diets has been strongly linked to their high levels of micronutrients particularly zinc, iron, calcium, and n-3 LC-PUFA.

Zinc deficiency remains a critical issue among non-pregnant and non-lactating women in Bangladesh (UNICEF, 2013) but our findings concurred with the sufficiency reported elsewhere (Combs et al., 2008) that was linked to high levels and bioavailability in fish-rich diets. Although estimated iron intake was below RNIs, the prevalence of iron deficiency is low because of high levels in the ground water (Rahman, 2016). In contrast, the low dietary calcium intake observed in our study was related to both low dairy consumption and reduced consumption of small indigenous fish species (SIS) in SE Bangladesh (Combs and Hassan, 2005). Both livestock and milk production are believed to have declined significantly in shrimp farming areas, in line with limited land available for grazing (Rahman et al., 2002). However, milk consumption in the current study was not correlated with saline gradients or socioeconomic status. Small fish eaten whole including the (soft) bones are a particularly valuable source of calcium (Roos et al., 2003a), however, a large range in calcium content among small indigenous species (60–1,480 mg Ca/100 g edible portion) has been reported (NIH, 2016) in Bangladesh. The relative decline in their consumption has been linked to the increased production of a limited range of farmed fish (Belton et al., 2014). However, no monoculture was observed in the study area and the diversity of aquatic animals produced and consumed was high.

Differential access to and consumption of fish are likely to explain the variable n-3 LC-PUFA levels among adolescent females in the current study. Higher n-3 LC-PUFA levels are a result of higher consumption levels of n-3 LC-PUFA rich aquatic animals in HS/MS sites, compared with LS/FW sites. The strong link between the n-3 LC-PUFA content in aquatic

animals and in females' whole blood levels demonstrated that local food production could influence the omega-3 index status of dependent communities as a whole rather than being limited to those who, as farmers, had direct access to the means of production. Consumption of small, unstocked, self-recruiting tilapias and indigenous species was particularly high in HS/MS communities, where the highest n-3 LC-PUFA blood levels were observed. Tilapia, globally most widely commonly raised in freshwater environments, has been criticized as a farmed species choice on the basis of a comparably low n-3 LC-PUFA content, and increasing levels has become a focus for contemporary diet formulation (Stoneham et al., 2018). This is in spite of an otherwise high nutrient content, including total lipid, protein, and micronutrients, like zinc (Karapanagiotidis et al., 2010). More favorable ratios of n-3:n-6 PUFA were found in less intensively farmed tilapia (Karapanagiotidis et al., 2006); however, the higher levels of EPA+DHA ($\text{g} \cdot 100\text{g}^{-1}$) found in saline-raised tilapia in the current study are unique and have impacted positively on human nutritional outcomes. The dietary contribution of micronutrients from small indigenous species is well-established for freshwater systems (Larsen et al., 2000; Gibson and Hotz, 2001; Roos et al., 2007). Relative connectivity of culture ponds to tidal water channels and availability of SIS originating from the Sundarbans mangrove forest probably explain their variable but greater importance in diets in the higher saline gradients: While the MS area was also close to the mangroves, it had limited SIS (just above half of HS area) due to poor connectivity of *ghers* to tidal water channels. This limitation appears to explain this area's reliance on introduced tilapias as a response to limited availability of mangrove-derived SIS. Tilapia accounted for 75–80% of the fish eaten by households in the HS community in another study in the same area (Faruque et al., 2016).

The importance of the “hidden harvest” of micronutrient-rich fish harvested from aquaculture, albeit that considered commercial, export-focused shrimp systems, parallels the term used for the under-reporting of yield, and nutritional significance, of freshwater fisheries (Fluet-Chouinard et al., 2018). The lack of any difference in n-3 LC-PUFA biomarker status between better-off and worse-off adolescent females also challenges the assumption that commercial aquaculture necessarily benefits the better-off at the expense of the poor (Belton et al., 2017; Nguyen et al., 2018). The impact of commercialization on the nutrition of smallholder farmers is, in general, under-researched (Ogutu et al., 2019), and nutrition-sensitive food production requires support, even in cash cropping contexts (Rukmani et al., 2018). Our study demonstrates undocumented complexity and diversity in commercial, export-driven aquaculture systems in Bangladesh and highlights their potential nutritional benefits for vulnerable adolescent females.

CONCLUSION

This work has quantified and described the heterogeneity of consumed seafood at an intra-household level, identifying

continued inequalities and highlighting the need for targeted measures to improve consumption of nutritious food by vulnerable adolescent females across the socioeconomic spectrum. The finding that individuals located in freshwater areas maybe at greater risk of nutrition insecurity than those in more saline locations is novel; the diversity of integrated pond-dyke cropping in less saline and freshwater gradients has been correlated with increased dietary diversity but our results challenge this orthodoxy and have implications for targeting of interventions. Policy that supports less intensive polycultures that are both compatible with high quality export-orientated shrimp and production of affordable, nutritionally high-quality seafood for local people should be developed. The nutritional and broader livelihoods outcomes of extensive polycultures are underappreciated and are vulnerable to trends in global trade. Among its critics, a common perception of the Bangladesh shrimp sector is that it operates on an “industrial scale” with external investors being the main producers on consolidated land holdings. However, though commercial in orientation, the aquatic farming systems in SW Bangladesh remain smallholder-managed and clearly support household subsistence needs and local nutritional security. Furthermore, the diversity of the systems, highly influenced by prevailing salinity, has broader impacts on local food systems. Although increasing salinity may restrict production of rice and other terrestrial crops, *gher* dykes have given rise to significant production of high-value vegetables where the salinity of water remains low. This study also provides evidence for the linked value of conservation of the Sundarbans in sustaining proximate extensive aquaculture. Wild juveniles deriving from these enduring resources form a key part of the environmental services they provide.

DATA AVAILABILITY STATEMENT

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found at: <https://dspace.stir.ac.uk/handle/1893/25012#.YILTzKFDY2w>.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Bangladesh Medical Research Council (BMRC). Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin. The animal study was reviewed and approved by Bangladesh Medical Research Council and University of Stirling, UK.

AUTHOR CONTRIBUTIONS

A-AM, DL, and FM designed the research. A-AM, BM, and DL analyzed the data. All authors wrote the paper.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fsufs.2021.713140/full#supplementary-material>

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