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Research Article Araştırma Makalesi

Small-Scale Rainbow Trout Cage Farm in the Inland Waters of Turkey is Sustainable in Terms of Carbon Footprint (kg CO_2e)

Türkiye İç Sularında Küçük Kapasiteli Gökkuşağı Alabalığı Kafes Yetiştiriciliği Karbon Ayak İzi Bakımından Sürdürülebilirdir

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Abstract: As a climate change assessment criterion, carbon footprint CO_2 *equivalent* (CF, CO_2e) is used to evaluate the sustainability of aquaculture in terms of its contribution to greenhouse gas emissions. In this study, the three-year CF of rainbow trout production with a cage farming project capacity of 49 tonnes/year was calculated. The average production capacity of the farm for three years was 52.72 %. Total CF expended was the summation of CF expended on feed, general management, transportation, machinery, and equipment. CF expended on the consumed compound diet had the highest contribution to total CF with 73.69 %. The second highest contributor to total CF was general management with a share of 13.08 % and, of this amount, diesel and labor constituted 78.49 and 19.36 % of it, respectively. Total CF expended per kg and 1 000 fish was 1.13 and 292.52 kg CO_2e. Mean values for CF expended per kg carcass, per Mcal energy deposited in the carcass, and per kg of protein deposited in carcass were 1.40, 1.48, and 9.43 kg CO_2e, respectively. On average, CF expended per Mcal of cultural energy expended during production was 0.35 kg CO_2e. The mean of CF of FCR*e*, defined as total CF of consumed compound diet divided by total liveweight gain was 0.99 kg CO_2e. Results showed that aquaculture is a low carbon-emitting sector thus is sustainable and this advantage should be considered when meeting people's protein demand.

Keywords
- cage
- carbon footprint
- CO_2
- rainbow trout
- sustainability

Özet: İklim değişikliği değerlendirme kriteri olarak karbon ayak izi CO_2 *eşdeğeri* (KAİ, CO_2e), su ürünleri yetiştiriciliğinin sera gazı emisyonuna yaptığı katkı bakımından sürdürülebilirliğinin değerlendirilmesinde kullanılır. Bu çalışmada, 49 ton/yıl kafes yetiştiriciliği proje kapasitesine sahip gökkuşağı alabalığı üretiminin üç yıllık KAİ değerleri hesaplanmıştır. Çiftliğin üç yıllık ortalama üretim kapasitesi 52,72%'dir. Harcanan toplam KAİ değeri, yem, genel yönetim, taşıma, makine ve ekipman için harcanan KAİ'nin toplamından oluşmuştur. Toplam KAİ değeri içinde karma diyet için harcanan KAİ, % 73,69 oranıyla en yüksek seviyede bulunmuştur. Toplam KAİ içinde ikinci en yüksek katkıyı % 13,08'lık pay ile genel yönetim oluşturmuştur ve bu katkıdaki dizel ve işçiliğin payı sırasıyla % 78,49 ve % 19,36 olarak bulunmuştur. Kg ve 1 000

Anahtar kelimeler
- kafes
- karbon ayakizi
- CO_2
- gökkuşağı alabalığı
- sürdürülebilirlik

balık başına harcanan toplam CF 1,13 ve 292,52 CO2*e* olarak hesaplanmıştır. Kg karkas, karkasta biriken Mcal enerji ve karkasta biriken kg protein başına harcanan KAİ değerleri sırasıyla 1,40, 1,48 ve 9,43 kg CO_2e olarak bulunmuştur. Üretim döneminde harcanan her Mcal kültürel enerji başına düşen KAİ değeri 0,35 kg CO2*e* olarak tespit edilmiştir. Tüketilen karma diyetin toplam KAİ'sinin toplam canlı ağırlık kazancına bölünmesiyle tanımlanan FCR*e* için KAİ değeri 0.99 kg CO_2e olarak hesaplanmıştır. Sonuçlar, düşük karbon yayan bir sektör olan su ürünleri yetiştiriciliğinin sürdürülebilir olduğunu ve insanların protein talebini karşılarken bu avantajın göz önünde bulundurulması gerektiğini göstermiştir.

1. INTRODUCTION

In parallel with the increase in world aquaculture, aquaculture in Turkey is also increasing (FAO, 2021; GDFA, 2021). World rainbow trout (*Oncorhynchus mykiss* Walbaum, 1792) production of 495 727 tonnes in 2000 increased by 84.89% in 2019 and reached 916 540 tonnes (FAO, 2021). The production of Turkish rainbow trout farming of 44 533 tons in 2000 increased by 223.76 % and reached 144 182 tonnes in 2020 (GDFA, 2021). According to the 2019 data, Turkey holds 2nd place with 13.43 % of the global rainbow trout production (FAO, 2021). In 2021, rainbow trout production constituted 34.21 % of Turkey’s aquaculture production (GDFA, 2021).

The biggest source having an impact on climate change, which is defined as long-term changes in the atmosphere, is anthropogenic fossil fuels (UN, 2021). Greenhouse gas (GHG) emissions that cause climate change result in the accumulation of heat near the Earth’s surface atmosphere (Shahid and Behnassi, 2014; UN, 2021). Some of the heat reflected from the Earth is captured by the GHGs in the atmosphere and re-radiated back to the Earth’s surface, causing a temperature rise, potentially causing climate damage (Shahid and Behnassi, 2014). Greenhouse gases that absorb infrared radiation in the atmosphere include water vapor, carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride (Shahid and Behnassi, 2014). And these emissions are mainly from energy, industry, transportation, agriculture, and land use (UN, 2021). Based on the monitoring of the effects of climate change, the unit of measure of carbon footprint (CF) resulting from materials entering the system is calculated in terms of CO_2 equivalents (CO_2e) per product (Alley et al., 2007; Weidema et al., 2008; Liu et al., 2016). GHG emissions during the production, transportation, processing, and storage of fisheries and aquaculture activities are low, but it still contributes to GHG emissions (Cochrane et al., 2009). However, there are significant differences in emissions for sub-sectors and types of cultures. Considering the current practices, the CF of aquaculture can be improved (Cochrane et al., 2009). In this respect, in the face of operational changes in aquaculture and increasing production efficiency due to intensive production systems, determining the CF that reduces GHG in terms of environmental and sustainability should be evaluated in connection with meeting the global demand for protein and food safety (Boyd et al., 2020). It has been reported that life cycle assessments of aquaculture and studies examining some socioeconomic indicators and environmental effects have significant potential in producing recommendations and policies for the blue growth of the aquaculture industry. Based on this, it was recommended that the aquaculture industry, which is dependent on the environment, should be supported by public policies within the scope of its sustainable goals, and in this context, similar studies should be carried out on future forecasts of food grown to make more consistent recommendations to policymakers (Henriksson et al., 2017). While the CF of aquaculture is lower than that of beef and pork farming, it is similar to or lower than that of poultry (Sonesson et al., 2010). Aquaculture with a low CF is a potential production area in terms of sustainability. In addition, cage farming has low investment and energy costs, relatively low environmental impacts, and a lower CF than other systems in terms of protein production (Angel et al., 2019). Although Raul et al., (2020) reported that there is no clear data on the total GHG emissions of aquaculture as GHG emission source or the GHG emissions of culture systems. Hu et al. (2016) stated that GHG emission from aquaculture in 2009 was 9.30 x 10^{10} g CO_2e and this will increase to 3.83 x 10^{11} g CO_2e in 2030 which will account for 5.72 percent of anthropogenic N_2O emissions. The total GHG emissions of bivalves, catfish, cyprinids, freshwater fish, Indian major carps, marine fish, salmonids, shrimps and prawns, and tilapias which accounted for 93 % of aquaculture production in 2017 were calculated as 245 $MtCO_2e$. Considering that the remaining 7 % of production would have the same emission intensity, total emissions would be estimated as 263 $MtCO_2e$. Based on an estimate of 53.5 $GtCO_2e$/year of total anthropogenic emissions in 2017, aquaculture accounts for approximately 0.49 % of total anthropogenic emissions (MacLeod et al., 2020).

Literature review showed that even though there have been studies examining the sustainability of aquaculture in terms of cultural energy use in Turkey (Diken et al., 2021), there is a lack of studies examining the sustainability of aquaculture in terms of CF. Thus, the purpose of this study was to evaluate the CF of small-scale rainbow trout cage farms in the inland waters of Turkey and to produce some suggestions for policymakers and producers in Turkey.

2. MATERIAL AND METHOD

2.1. Management of rainbow trout:

This study is a follow-up study determining the carbon footprint (CF) of small-scale rainbow trout cage farms in the inland waters of Turkey and it stemmed from data used in Diken et al. (2021) study. Thus in order not to repeat it, feeding, rearing, and management information of rainbow trout can be followed in the aforementioned article. However, for readers' information summary of feeding and rearing information is provided in Table 1.

2.2. Carbon footprint (kg CO_2e) analysis:

The CF (kg CO_2e) inputs and outputs of cage farmed trout were calculated according to the unit values in Table 2. The proximate composition of Diet-1 used consisted of 46 % crude protein (CP), 19 % crude oil (CO), 10 % crude ash (CA), 1.5 % crude fiber (CF), and had 4 000 Mcal ME kg^{-1}. Proximate composition of Diet-2, 3 and 4 consisted of 45 % CP, 20 % CO, 9.5 % CA, 1.7 % CF, and 4 000 Mcal ME kg^{-1}. Considering proximate composition information, the diets were formulated according to feed ingredients (fish meal, fish oil, soybean meal, wheat grain, wheat by-products, vitamins, and minerals) provided in the prospectus (Table 3). The CF values of Diet-1, 2, 3, and 4 were calculated by multiplying the number of feed ingredients by the unit value (kg CO_2e) obtained from the literature (Table 4). In addition to CF coming from feed ingredients, CF for pelleting which sums to 0.13 kg CO_2e per kg (Hognes et al., 2011) was also added to CF coming from feed ingredients to find the total CF of diet which summed to 0.97 kg CO_2e per kg (Table 4).

Table 1. Feeding and rearing information of rainbow trout.

Feeding days	T (^{0}C)	W/w Size (g)	W/w Σ (kg)	Number of RT Stock	Number of RT Live	Number of RT Dead	Diets No/ kg	A&V (kg)	FCR
First-year									
Rearing Period (days): 120-150 / Stock (m^3): 50 fish&1.70 kg (initial), 32.50 fish&9.33 kg (harvest)									
30	14-16	30-50	4 250	125 000	122 000	3 000	D1/ 5 000		1.05
30-60	14-10	60-120	9 000	122 000	121 948	52	D2/ 7 500		1.0
60-90	9-10	120-180	16 500	121 948	121 915	33	D3/ 9 000	5&5	1.0
90-120	9-12	150-200	25 500	121 915	121 877	38	D4/10 000		1.05
120-150	12-16	200-250	35 000	121 877	121 800	77	**Σ** 31 500		1.02
Second-year									
Rearing Period (days): 130-160 / Stock (m^3): 38 fish&1.71 kg (initial), 24.52 fish&6.00 kg (harvest)									
30	13-15.5	45	4 275	95 000	92 150	3 850	D1/ 3 000		1.0
30-60	13-10	60-85	7 275	92 150	92 000	150	D2/ 4 000		1.0
60-100	9-10	100-135	11 250	92 000	91 975	25	D3/ 5 000	5&7.5	1.0
90-130	9-12	150-180	16 250	91 975	91 968	7	D4/ 6 250		1.0
130-160	12-14	200-250	22 500	91 968	91 950	18	**Σ** 18 250		0.99
Third-year									
Rearing Period (days): 150-175 / Stock (m^3): 34 fish&1.60 kg (initial), 21.93 fish&5.33 kg (harvest)									
30	12-15	25	4 000	85 000	82 300	2 700	D1/ 2 500		0.94
30-50	12-10	50-60	6 500	82 300	82 277	23	D1/ 2 000		
50-80	9-11	80-120	8 000	82 277	82 255	22	D2/ 4 000	4&5	1.0
80-120	12-14	100-150	12 000	82 255	82 250	5	D3/ 4 000		1.0
120-150	14-15	200-250	16 000	82 250	82 250		D4/ 4 250		0.94
150-175	16	250	20 000				**Σ** 16 750		0.96

Description; RT; rainbow trout, First-year (2016-2017), Second-year (2017-2018), Third-year (2018-2019), DAH; days after hatching, W/w; wet weight, ΣW/w; total wet weight, T; temperature, Diets; commercial diet-D1 (46% CP and 19% CO) D2, D3, D4 (45% CP and 20% CO) A&V; antibiotic & vitamin.

The CF expended for the consumed compound diet was calculated by multiplying the total kg of each diet consumed and the CF values of each diet. A similar approach was also applied in calculating the CF expended for general management, transportation, machinery, and equipment. The CF expended for general management included the CO_2e expended for antibiotics, vitamins, labor, diesel, and oxygen. While calculating the CF expended for transportation, the distance between the hatchery and the farm, the number of fingerlings transported to the farm was taken into account. The CF expended on machinery and equipment was calculated by multiplying the amount of machinery and equipment by the kg CO_2e value of the item and dividing it by its depreciation rate. Total CF expended was the summation of CF expended on feed, general management, transportation, machinery, and equipment (Table 5). While calculating the energy content of the carcass and fillet, the methodology given in Diken et al. (2021) was used. Some calculations used in the study are as follow:

CF expended for kg liveweight gain = total CF expended / weight gain during the feeding period.

CF expended per kg marketed carcass = total CF expended / (total final weight x dressing percentage of carcass).

CF expended per kg marketed fillet = total CF expended / (total final weight x dressing percentage of fillet).

CF expended per Mcal energy deposited in harvested fish = total CF expended / energy deposited in harvested fish during feeding.

CF expended per Mcal energy deposited in carcass = total CF expended / energy deposited in carcass during feeding.

CF expended per Mcal energy deposited in fillet = total CF expended / energy deposited in fillet during feeding.

CF expended per kg of protein deposited in harvested fish = total CF expended / total amount of protein accumulated in the harvested fish.

CF expended per kg of protein deposited in carcass = total CF expended / total amount of protein accumulated in the carcass.

CF expended per kg of protein deposited in fillet = total CF expended / total amount of protein accumulated in the fillet.

CF expended per Mcal of cultural energy expended during production = total CF expended / total cultural energy expended.

CF of FCR*e* = total CF of consumed compound diet / total liveweight gain.

CF input for total production, kg, and 1 000 harvested/marketed fish and output for production years are provided in Table 5.

3. RESULTS AND DISCUSSION

This study was conducted at a private farm having a full capacity of 49 tonnes/year, however, the farm used 71.43, 45.9, and 40.82% of its full capacity for the first, second and third year, respectively with an overall average of 52.72% (Table 1). Our overall capacity use (52.72%) was similar to that of the project capacity of inland waters of Turkey which was 59.86% (GDFA, 2021).

CF input for total production, kg, and 1 000 harvested/marketed fish are given in Table 5. CF expended on the compound diet per kg of harvested/marketed fish for the first, second, third year, and the mean of three years was 0.87, 0.78, 0.81, and 0.82 kg CO_2e, respectively. When Figure 1 is examined, it is observed that CF expended on consumed compound diet constituted 79.59, 71.73, and 66.42 % of total kg CO_2e expenditure for first, second and third year, respectively.

CF shares of Diet-1, 2, 3, and 4 in CF expended on consumed compound diet are given in Figure 2. Compared to the third year, an increasing trend was observed in the CF shares of the compound diets consumed in the first and second years. The reason for this is that in the third year, the initial stocking weight of rainbow trout fingerlings was much lighter (Table 1), thus third-year fingerlings consumed a higher amount of Diet-1. Depending on the fish growth, as the feed consumption increases an increase in CF expended on the compound diet is observed (Figure 2). Ziegler et al. (2021) found that in salmon production, feed constituted 85 % of total CF which had a higher ratio than ours, however, in our study the farm did not use its full capacity.

Considering that CF expended on general management, transportation, machinery, and equipment would not increase much as the farm used full capacity, it would be assumed that if the farm used its full capacity, the share of feed in total CF would increase and reach reported by Ziegler et al. (2021). CF expended on the general management per kg of harvested/marketed fish and per 1 000 harvested/marketed fish is provided in Table 5.

Table 2. Carbon footprint (kg CO_2e) values for inputs and outputs of the rainbow trout cage rearing.

Items	Unit		References
Inputs		MCal unit^{-1}	
Fish fingerling	kg	1.45	Calculated according to Mehrabi et al. (2012)
Inputs		kg CO_2e unit^{-1}	
Feed & feed ingredients			
fish meal	kg	0.99	Hognes et al. (2011)
fish oil	kg	0.99	Hognes et al. (2011)
soybean meal	kg	0.541	Moe et al. (2014)
wheat grain	kg	0.51	Hognes et al. (2011)
wheat middlings	kg	0.306	Vellinga et al. (2013)
vitamin	kg	1.62	Rotz et al. (2019)
mineral	kg	1.62	Rotz et al. (2019)
pellets production	kg	0.13	Hognes et al. (2011)
Diet-1	kg	0.97	Calculated
Diet-2, 3, 4	kg	0.97	Calculated
Antibiotic	kg	2.02	Ecoinvent database V3.4
Vitamin	kg	1.62	Rotz et al. (2019)
Labour	h	0.70	Nguyen and Hermansen (2012)
Diesel	L	3.11	Robertson et al. (2015)
Oxygen	kg	0.2865	Šulc and Ditl (2021)
Transportation	tonne.km	0.722	Robertson et al. (2015)
Cage net and rope	kg	8.13	Ecoinvent database V3.4
Iron	kg	3.98	Qi et al. (2018)
Boat (*sheet iron*)	kg	2.45	Ecoinvent database V3.4
Boat (*engine iron*)	kg	3.98	Qi et al. (2018)
Styrofoam flotation	kg	6.735	Sivakkumar et al. (2020)
Vault (*cement*)	kg	0.208	Henry et al. (2014)
Vault (*iron*)	kg	3.98	Qi et al. (2018)
Outputs (per kg of processed fish as)		MCal unit^{-1}	
Harvested fish		1.93	Calculated according to Welker et al. (2018)
Carcass		1.02	Calculated according to
Fillet		0.72	Tatıl (2019)

The mean of three years for CF expended on the general management per kg of harvested/marketed fish and per 1 000 harvested/marketed fish was 0.16 and 39.46, respectively. CF expended on the general management constituted 10.23, 15.13, and 15.46% of total CF expenditure for the first, second, and third year, respectively. CF expended on general management was composed of diesel, labor, oxygen, antibiotics, and vitamins used and each item’s share in CF expended on general management was 78.49, 19.36, 1.66, 0.25, and 0.24 %, respectively (Figure 3).

Table 3. Proximate composition of feed ingredients and formulation of compound Diet-1 and Diet-2, 3, and 4*.

P	**Fish meal**	**Fish oil**	**Soybean meal**	**Wheat grain**	**Wheat middlings**	**Vitamin**	**Mineral**	**∑**
Proximate composition of feed ingredients								
CP	66.95	0	46.40	13.08	15.81			
CO	8.83	100	1.09	2.10	3.00			
CA	15.40	0	7.95	2.06	3.64	100	100	
CF	0.70	0	6.08	3.11	6.97			
ME	3 559	8 766	2 712	2 789	2 623			
Constituent of Diet-1 providing (46.0% CP, 19.43% CO, 10.86% CA, 2.16% CF, 3 994.60 ME kg^{-1})								
%	50.47	14.48	23.15	9.23	1.67	0.50	0.50	
CP	33.79	0	10.74	1.21	0.26			46.00
CO	4.46	14.48	0.25	0.19	0.05			19.43
CA	7.77	0	1.84	0.19	0.06	0.50	0.50	10.86
CF	0.35	0	1.41	0.29	0.12			2.16
ME	1 796.23	1 269.32	627.83	257.42	43.80			3 994.60
Constituent of Diet-2, 3, and 4 providing (44.99% CP, 20.08% CO, 10.69% CA, 2.11% CF, 4 031.97 ME kg^{-1})								
%	50.31	15.12	20.54	10.36	2.67	0.50	0.50	
CP	33.68	0	9.53	1.36	0.42			44.99
CO	4.44	15.12	0.22	0.22	0.08			20.08
CA	7.75	0	1.63	0.21	0.10	0.50	0.50	10.69
CF	0.35	0	1.25	0.32	0.19			2.11
ME	1 790.53	1 325.42	557.04	288.94	70.03			4 031.97

*Diet-1 (46% CP, 19% CO, 10% CA, 1.5% CF, 4 000 Mcal ME kg^{-1}), and Diet-2, 3, and 4 (45% CP, 20% CO, 9.5% CA, 1.7% CF, 4 000 Mcal ME kg^{-1}). The proximate composition of the feed ingredients is taken from IAFFD (2020) and the proximate compositions of the formulation are arranged. P: proximate; CP: crude protein; CO: crude oil; CA: crude ash; CF: crude fiber; ME: metabolic energy. The difference is reflected in the calculation due to rounding.

Table 4. Carbon footprint (kg CO_2e) value of kg of Diet-1, 2, 3, and 4*.

FI	**CO_2e value (kg CO_2e kg^{-1}) (A)**	**Diet-1 Percent in compound diet (B)**	**Diet-1 Value (kg CO_2e kg^{-1}) (A*B)/100**	**Diet-2, 3, 4 Percent in compound diet (C)**	**Diet-2, 3, 4 Value (kg CO_2e kg^{-1}) (A*C)/100**
FM	0.99	50.47	0.50	50.31	0.50
FO	0.99	14.48	0.14	15.12	0.15
SM	0.541	23.15	0.13	20.54	0.11
WG	0.51	9.23	0.05	10.36	0.05
WM	0.306	1.67	0.01	2.67	0.01
V	1.62	0.50	0.01	0.50	0.01
M	1.62	0.50	0.01	0.50	0.01
PP	0.13		0.13		0.13
		Σ	0.97	Σ	0.97

*FI: feed ingredients; FM: fish meal, anchovy; FO: fish oil; SM: soybean meal; WG: wheat grain; WM: wheat middlings; V: vitamin; M: mineral; PP; pellets production. The difference is reflected in the calculation due to rounding.

Table 5. Carbon footprint (CF, kg CO_2e) input for total production, kg and 1 000 harvested/marketed fish and output for production years.

Items	Unit*	First-year	Second-year	Third-year	Mean
CF expended on consumed compound diet	Total	30 434.39	17 632.68	16 184.37	21 417.15
	kg	0.87	0.78	0.81	0.82±0.04
	1 000 fish	249.87	191.76	196.77	212.80±32.20
CF expended on general management	Total	3 913.52	3 718.85	3 767.67	3 800.01
	kg	0.11	0.17	0.19	0.16±0.04
	1 000 fish	32.13	40.44	45.81	39.46±6.89
CF expended on transportation	Total	779.76	116.96	1 299.60	732.11
	kg	0.02	0.01	0.06	0.03±0.03
	1 000 fish	6.40	1.27	15.80	7.82±7.37
CF expended on machinery and equipment	Total	3 113.66	3 113.66	3 113.66	3 113.66
	kg	0.09	0.14	0.16	0.13±0.03
	1 000 fish	25.56	33.86	37.86	32.43±6.27
Total CF expended	Total	38 241.34	24 582.15	24 365.30	29 062.93
	kg*	1.09	1.09	1.22	1.13±0.07
	1 000 fish	313.97	267.34	296.23	292.52±23.53
CF expended for compound diet, Mcal day^{-1}	Total	255.75	136.69	112.39	168.28
	kg	0.01	0.01	0.01	0.01±0.01
	1 000 fish	2.10	1.49	1.37	1.65±0.39
CF expended per kg liveweight gain		1.24	1.35	1.52	1.37±0.14
CF expended per kg marketed carcass		1.35	1.35	1.50	1.40±0.09
CF expended per kg marketed fillet		1.90	1.90	2.12	1.97±0.13
CF expended per Mcal energy deposited in harvested fish		0.62	0.66	0.74	0.68±0.06
CF expended per Mcal energy deposited in carcass		1.30	1.47	1.68	1.48±0.19
CF expended per Mcal energy deposited in fillet		2.00	2.45	2.82	2.42±0.41
CF expended per kg of protein deposited in harvested fish		7.45	8.08	9.12	8.21±0.84
CF expended per kg of protein deposited in carcass		8.55	9.27	10.47	9.43±0.97
CF expended per kg of protein deposited in fillet		12.04	13.06	14.75	13.28±1.37
CF expended per Mcal of cultural energy expended during production		0.35	0.35	0.36	0.35±0.01
CF of FCR*e*		0.99	0.97	1.01	0.99±0.02

*CF: expended per kg harvested fish. SD: standard deviation. The difference is reflected in the calculation due to rounding.

CF expended on transportation per 1 000 harvested/marketed fish for the first, second, the third year, and the mean of three years was 6.40, 1.27, 15.80, and 7.82 Mcal, respectively (Table 5). CF expended on transportation varied among production years and the reason for this was that as mentioned in the materials and methods section, the distance of hatchery varied for years and compound diet was delivered to the farm, and fish were harvested/marketed at the farm meaning that no transportation was involved. Total CF expended on machinery and equipment was the same for three years as each year the same amount of machinery and equipment is used. However, when CF is reported for per kg of harvested/marketed fish and per 1 000 harvested/marketed fish, on average it was 0.13 and 32.43, respectively (Table 5). CF expended on general management and machinery and equipment per kg of harvested/marketed fish and per 1 000 harvested/marketed fish were lowest for the first year and highest for the third year and the reason for this was that production amount decreased as the year proceeded. Considering that CF expended on machinery and equipment is the same for three years and meaning that it does not change with the production capacity, using a full capacity of 49 tonnes a year would decrease CF per kg of harvested/marketed fish to 0.06. This brings the importance of using full production capacity.

Total CF expended was the sum of CF expended on the compound diet, general management, transportation, machinery, and equipment. Total CF expended per kg of harvested/marketed fish for first, second, the third year, and the average of three years was 1.09, 1.09, 1.22, and 1.13 kg CO_2e, respectively. And total CF expended per 1 000 harvested/marketed fish for the first, second, third year and the mean of three years was 313.97, 267.34, 296.23, and 292.52 kg CO_2e, respectively. In a study determining resource use efficiency and estimation of carbon and water footprints in fish farming systems using life cycle analysis, Hagos (2012) found that cobia cage farm had the highest CF at 8 kg CO_2e/kg fish output, whereas Asian sea bass recirculation farm had the lowest CF at 1.7 kg CO_2e/kg fish output.

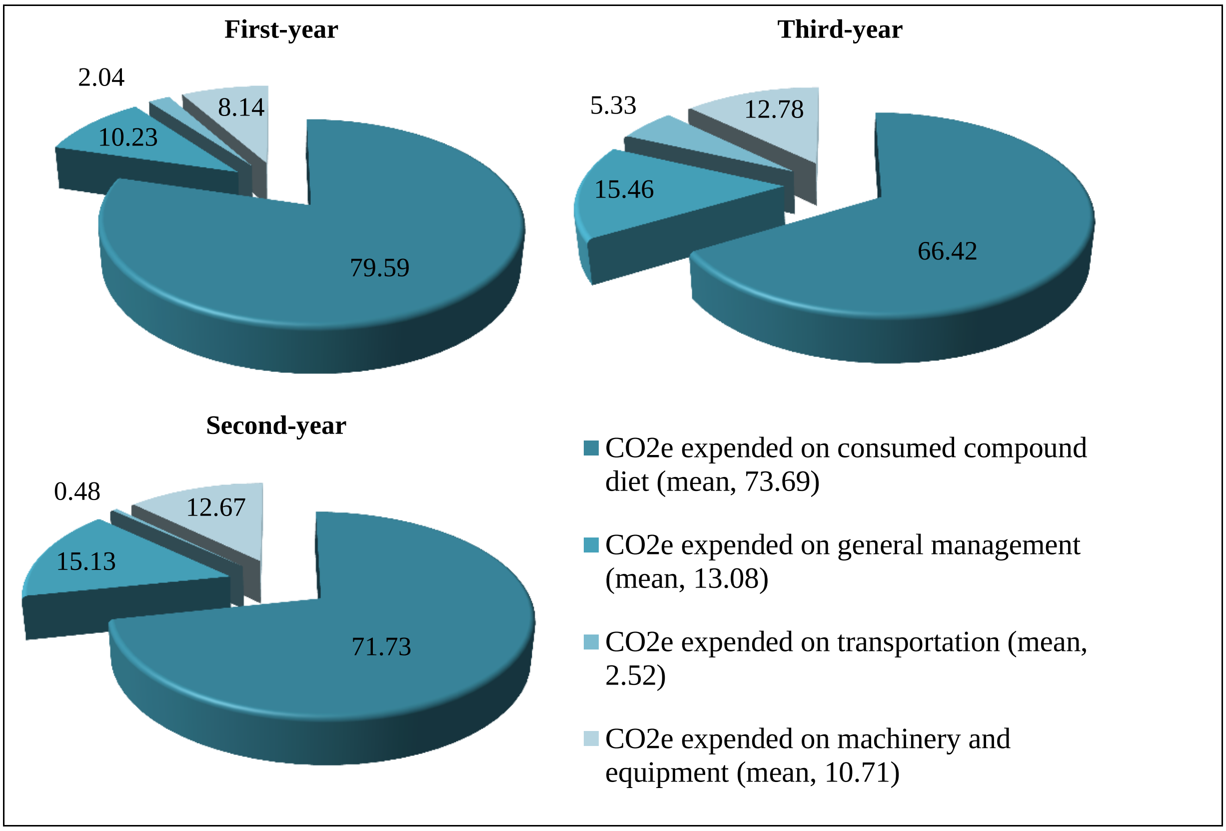

Figure 1. Carbon footprint (kg CO_2e) shares the total expended carbon footprint (kg CO_2e) according to the three-year values (%).

CF expended for a kg of liveweight gain for the first, second and third year was 1.24, 1.35, and 1.52, respectively. It was observed that as the farms had higher use of full capacity, they had lower values for CF expended for a kg of liveweight gain. Pelletier and Tyedmers (2007) reported that cultured Atlantic salmon required 1.2-2.7 kg of CO_2e per kg liveweight and their results were similar to ours.

CF expended for a kg of carcass and fillet on average was 1.40 and 1.97, respectively, and this value was in agreement with Boyd (2013) who reported that CF for per kg of meat for aquacultured fish was 2-7 kg CO_2e/kg meat. On the other hand, Robb et al. (2017) reported similar values to ours for the striped catfish culture system but lower values for carp culture and Nile tilapia. Our values were higher than those reported by Srinivasa et al. (2016) who researched the composite fish culture, shrimp culture, seabass, and by Kauffman et al. (2018) who researched shrimp in the pond. The reason for the difference in our and their values stem from the species used and production system. Our system was more intensive than theirs.

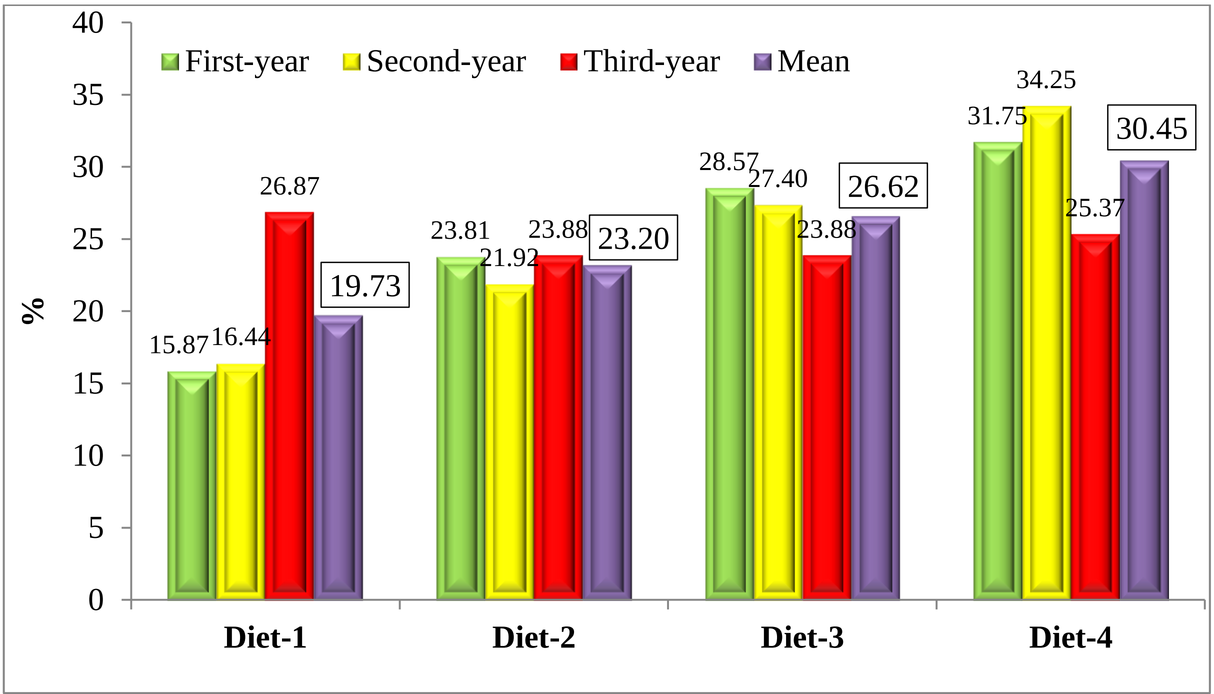

Figure 2. Carbon footprint (kg CO_2e) shares of Diet-1, 2, 3, and 4 in carbon footprint (kg CO_2e) expended on consumed compound diet (%).

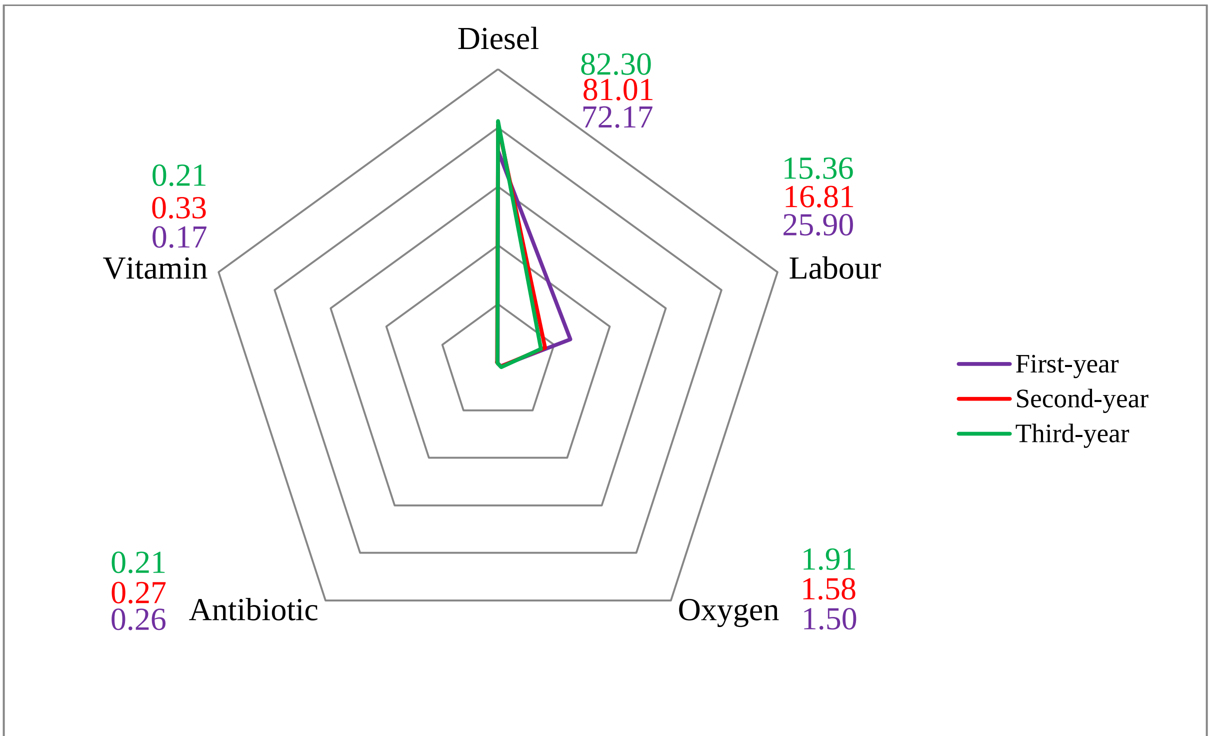

Figure 3. Contribution of each item to carbon footprint (kg CO_2e) expended on the general management (%).

CF expended for harvested fish was lower than that reported for sheep, beef, cow, pork, and poultry (Nemry et al., 2001; Rotz et al., 2010; Rotz et al., 2019). CF expended for kg marketed carcass was 1.35, 1.35, 1.50, and 1.40 for first, second, third year and the mean of three years, respectively (Table

5) and this was around 41 % higher than that expended for kg marketed fillet and the reason for this is the dressing percentage for carcass and fillet (81 % vs 57.5 %). Compared to CF expended for a kg of harvested fish, CF increased 24 and 74 %, as the harvested fish was processed into carcass and fillet (1.13 vs 1.40 vs 1.97). On average CF expended per Mcal energy deposited in harvested fish was 0.68, and this value increased 118 and 256 %, as the harvested fish was processed into carcass and fillet (0.68 vs 1.48 vs 2.42). On average CF expended per kg of protein deposited in harvested fish was 8.21, and this value increased 15 and 62 %, as the harvested fish was processed into carcass and fillet (8.21 vs 9.43 vs 13.28). Protein retention efficiency defined as the unit of protein produced per unit of protein fed was 31, 21, 18, and 15 %, for salmon, chicken, pork, and beef, respectively (MH, 2017), indicating that salmon produce twice the amount of protein as beef per unit of protein fed, therefore representing an attractive, alternative source of meat protein (Boyd et al., 2020). In our study, protein retention efficiency for harvested fish, carcass, and the fillet was around 36, 31, and 22 % respectively, showing that rainbow trout is also a good converter of feed protein into edible meat protein. According to the CF expended for the carcass and fillet, in terms of traceability of the CF, bringing the fillet waste products into the circular economy as a recycling source will support the sustainability of the blue economy.

CF expended per Mcal of cultural energy expended during production was on average 0.35, meaning that for each 2.86 Mcal cultural energy expenditure during the production period kg CO_2e was expended. This shows the interrelationship between carbon emission and cultural energy use as they both depend on external energy (fossil fuel) input. We propose the calculation of CF of FCR*e*, which is calculated as total CF of consumed compound diet / total liveweight gain, as an approach similar to the FCR value in the sustainability of aquaculture. With this approach, one can interrelate FCR with CF stemming from feed intake. The three-year mean of the CF of FCR*e* value was calculated as 0.99 kg CO_2e.

When the results of the study are compared with other sectors, it can be concluded that the aquaculture sector contributes little to GHG emissions (Swaminathan, 2012) and aquaculture can be considered as a low carbon economy (Pernet and Browman, 2021). Creating risk assessment reports of fisheries and aquaculture (Diken, 2020), covering plans for climate change adaptation studies (Kalıpcı et al. 2021), and determining the carbon footprint on a sectorial basis will be an important evaluation criterion for decision-makers in the protection and evaluation of aquaculture potential.

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There was no funding for the research.

CONFLICT of INTEREST

The authors declare that they have no conflict of interest

AUTHOR CONTRIBUTIONS

Other than data collection which was collected by İsmail Can and Gürkan Diken, other parts were equally shared by Gürkan Diken and Hayati Kaknöroğlu

ETHICAL STATEMENTS

In this study, animals are not used.

DATA AVAILABILITY STATEMENT

The data used to support the findings of this study are included in the article.

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