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Carbon footprint (kg CO_2e) expended in the aquaculture: An assessment of concrete pond rainbow trout farming from Türkiye

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ABSTRACT

The carbon footprint (CF) of animal production systems can be estimated by their standings against global protein demand. Türkiye is the largest producer of rainbow trout in Europe, but there is little data on its CF. This study aimed to evaluate the CF expended of concrete pond rainbow trout (CPRT) farming. The data were obtained from a farm with an annual project production capacity of 350 tonnes (APC) over a three-year production (TYP) with different harvest amounts. The total CF expended was the summation of CF expended on compound diets, general management, transportation and machinery, equipment, and construction. The total CF expended was calculated at 1.78 and 1.67 kg CO_2e on average for TYP and APC, respectively. The TYP average values of CF expended per kg of protein deposited in harvested/fresh weight fish and CF expended per Mcal of cultural energy expended during production were 10.66 and 0.36 kg CO_2e, respectively. The CF expended per 100 kcal food energy in harvested fish was calculated at 0.1263 and 0.1173 kg CO_2e on average for TYP and APC, respectively. Aquafeed production and transportation are the important CF expended sources in CPRT. Future studies must be species-specific and culture-specific.

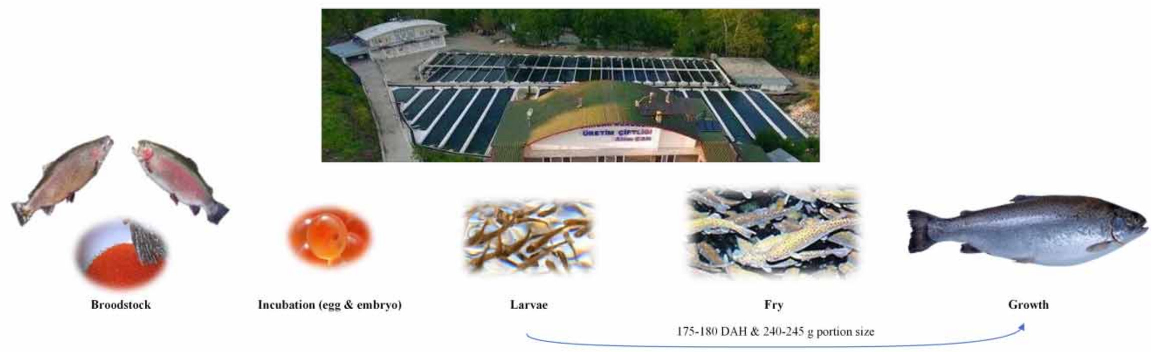
Key words: aquaculture, carbon footprint, kg CO_2e, rainbow trout, sustainability, Türkiye

HIGHLIGHTS

- The carbon footprint (CF) expended analysis of aquaculture is a reliable criterion for determining sustainability.
- Concrete pond rainbow trout farming generates over 80% of the CF for aquafeed and aquafeed transportation.
- The CF of the harvested rainbow trout for kg protein and calorie production was lower than that of farm animals.
- CF budget calculations should be standardized and made clearer for evaluations.

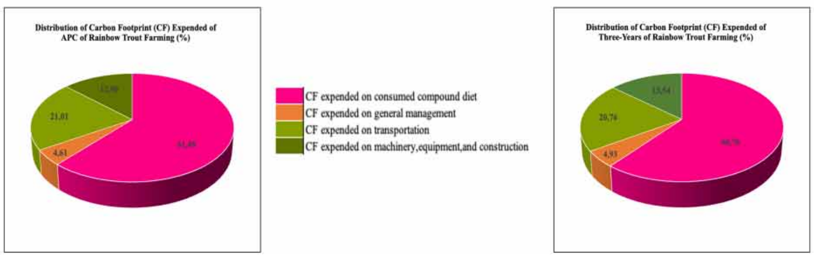
GRAPHICAL ABSTRACT

Carbon footprint (kg CO_2e) expended in the aquaculture: Assessment of concrete pond rainbow trout farming from Türkiye



Carbon footprint expended input and output for three-years average production per kg harvested/fresh weight/marketed fish (CF, kg CO_2e)

Items	Mean ± SD*	APC
Carbon footprint (CF) budget		
Total CF expended	1.78 ± 0.19	1.67
CF expendend for outputs		
CF expended per Mcal energy deposited in harvested fish gained during feeding	0.92 ± 0.10	0.85
CF expended per kg of protein deposited in harvested fish gained during feeding	10.66 ± 1.12	9.97
Cultural energy expended per Mcal of CF expended during production	2.57 ± 0.19	2.47
CF expended per 100 kcal food energy in harvested fish (kg CO_2e)	0.1263 ± 0.0134	0.1173



1. INTRODUCTION

The increase in the world population, which is expected to reach 10 billion by 2050, and the economic growth of developing countries will increase the demand for animal-derived protein such as meat, milk, and fish (Wu *et al.* 2014; NRC 2015). Global fisheries production, which has turned into an aquaculture-based food sector since 2013 (FAO 2022), is a qualified protein and fat source to meet the food demand in the face of the increasing world population. It is estimated that the thriving aquaculture sector will produce 62% of food fish by 2030 (TheWorldBank 2013). The sustainability of needs and demands for animal products should be supported by research on food safety (NRC 2015). As a reflection of increasing industrialization and developing technology, with the unplanned use of world resources, aquaculture has turned into an intensive production model aiming to obtain higher productivity per unit area, especially in countries with high industrial levels, in the face of increases in input costs. Especially, the production of carnivore finfish species is also included in these models. Türkiye, which makes a production based on these models, is an industrially important country in carnivorous finfish farming in the world and the Mediterranean Basin (FAO 2022). World production of rainbow trout (*Oncorhynchus mykiss*) from these species reached 916,540 tonnes in 2019 (FAO 2022). Türkiye, on the other hand, is the second country in world production after Iran, with 144,182 tonnes of rainbow trout production in 2020, and is the leading country in Europe and the Mediterranean Basin (GDFA 2021; FAO 2022).

The biggest source of climate change is greenhouse gas (GHG) emissions from anthropogenic fossil fuels, mostly from energy, industry, transportation, agriculture, and land use sectors (Shahid & Behnassi 2014; UN 2021; Islam *et al.* 2022a). The greenhouse effect of CO_2, which is one of the GHG emission sources, is 25% and its average residence time is approximately 100 years (Eggleton 2018). The carbon footprint (CF), an evaluation criterion in monitoring the effects of climate change, is calculated as CO_2 *equivalents* (CO_2e) per product (Alley *et al.* 2007; Weidema *et al.* 2008; Liu *et al.* 2016). For this reason, the sum of potential climate effects due to potential climate impact or global warming potential, GHG emission differences in food production systems and the amount of protein in the product, and global warming potential differences of GHG is considered a CO_2e measurement unit (ISO 2006a, 2006b; Shahid & Behnassi 2014; Liu *et al.* 2016; Weidema *et al.* 2008; IPCC 2022; Jones *et al.* 2022).

Seventy-seven per cent of the agricultural lands with a habitable land of 48 million km^2 of agriculture are livestock (meat and dairy) and 23% of agricultural lands are crops (excluding feed) agricultural land. The global protein support of these lands is 37% for meat and dairy and 63% for plant-based food (Ritchie & Roser 2019). As in all industries, the determination of strategies to reduce crop and crop-based GHG emissions and increase crop yields of the agricultural sector, and water management models that contribute to global warming potential on the basis of CO_2e, will make significant contributions to global climate change (Cheng *et al.* 2022; Islam *et al.* 2022a, 2022b). The share of livestock production with an annual CO_2e value of 8.1 Giga tonnes in total anthropogenic emissions is at the level of 14.5% (Gerber *et al.* 2013). In addition, if the transition from traditional diets to global diets based on industrial products is not controlled by 2050, an estimated 80% increase in world agricultural GHG emissions from food production and global land use is assumed (Tilman & Clark 2014).

Of the fisheries and aquaculture sources with low GHG emissions, aquaculture has a lower CF than beef and pork and similar to that of poultry (Cochrane *et al.* 2009; Sonesson *et al.* 2010; Boyd *et al.* 2020; Raul *et al.* 2020; D'Abramo 2021; Table 1). Low CF aquaculture is a potential production area in terms of each of the economic, social, and environmental sustainability principles that need to be addressed at a local, regional, and international scale, and CF values are at a level that can further be improved (Cochrane *et al.* 2009; Henriksson *et al.* 2013; Angel *et al.* 2019; Boyd *et al.* 2020). Aquaculture, which has an important potential to feed the world population, is included in the sustainable bioeconomy (Boyd *et al.* 2020). The strategic goal in food production should be based on the principles of sustainability and circular economy (Boyd *et al.* 2020; Hamam *et al.* 2021; Tacon *et al.* 2022; Viles *et al.* 2022). However, the potential stress effect of climate change can also have an impact on food security and nutrition, as the vulnerability of the system can be increased or decreased depending on vulnerabilities (Gitz *et al.* 2016). CF analysis can be considered as an approach within the scope of this purpose (Henriksson *et al.* 2017; Boyd *et al.* 2020; Rossi *et al.* 2021; Diken *et al.* 2022). For this purpose, in order to provide standardization in the CF assessments used in determining the potential situation of aquaculture in sustainability and climate change, kg CO_2 emission value per kg of the edible product obtained as a result of all activities should be calculated (Lutz 2021; Diken *et al.* 2022). In carrying out these studies, empirical studies from the feed and producer sectors are needed, especially in order to calculate aquaculture emissions (MacLeod *et al.* 2020).

Industry studies supported by scientific methods are evaluated with solution-oriented approaches against the devastating effects of global climate change originating from the Anthropocene. For this purpose, salmon farms have set innovation plans in feed, transportation, and operations as priority targets in line with the targets of reducing carbon emissions in efforts to tackle climate change (Hogan 2021). In order to ensure sustainability, the leading global aquafeed factories in world production have started their plans for environmentally friendly low-emission feed production. These management plans are low-emission feed production based on low-emission feed ingredients without decreasing feed quality (HatcheryFeedManagement 2021), and the other is the on-farm planning of feed production to reduce the CF values caused by transporting the feed to the farm (HatcheryInternational-Staff 2021). The second private company mentioned continues to work on the production of feed ingredients that enables the conversion of methane into protein-based solutions and feed formulation with 10% lower CF than standard diets, in line with its sustainability goals (EFA News 2022; HatcheryInternational Staff 2022). Another private company aims to reduce the CF of seafood farming by 30% by 2030, saving 2 billion kg of CO_2 per year (Cargill 2022).

In this study, in which the anthropogenic effects of aquaculture were determined, the CF expended of the rainbow trout farm, which was grown in concrete ponds using spring water, was evaluated and some suggestions were made to policymakers and producers.

2. MATERIALS AND METHODS

2.1. Management of concrete pond rainbow trout farming (CPRT)

This study is a follow-up study determining the CF (kg CO_2e) expended in concrete pond rainbow trout farming (CPRT) from Türkiye and it stemmed from data used in the study of Diken & Koknaroglu (2022). Rainbow trout farming and management information can be followed in the cited article. In of this study, ethical approval is not required as farm records were used.

Canlar Alabalık is located in Çandır Village of Sütçüler District in Isparta Province, which is located in the Lakes Region of Turkey (Figure 1). The farm using Göksu Stream spring water uses the flow-through water system technique in rainbow trout

Table 1 | General carbon footprint values of food-source aquaculture and farm animals (kg CO_2e)

Average daily dietary energy need per 					References
2,373 kcal for 1969–1971 and 2,950 kcal for 2020					Alexandratos & Bruinsma (2012) and FAO (2021)
3,025 kcal for forecast 2030					OECD/FAO (2021)
Total climate change values of aquaculture (CO_2e)					References
291.2 megaton (Mt) for 2008, 385 Mt for 2010 and 674.6 Mt for forecast 2030					Hall *et al.* (2011)
245 Mt for 2017, 93% of which is calculated, and a forecast 263 Mt with the remaining 7% the share of aquaculture species in total emissions is about 0.49% (263 Mt/53.5 Gt)					MacLeod *et al.* (2020)
Edible meat production value in kg					References
					
1.8–3.3	1.5–7	3–6		16–40	FEAP (2022)
3–15	2–6	4–11	10–50	9–129	Nijdam *et al.* (2012)
2–7 (4)	3–4	4–8		12–16	Boyd (2013)
	2.7	5.9		30	MH (2017)
	1.8	3.2	18.5	14.5	Nemry *et al.* (2001)
3.28					MacLeod *et al.* (2020)

farming. From the eggs taken from the broodstock by dry milking method, diploid rainbow trout were raised up to 175–180 DAH and an average of 240–245 g portion size. The water temperature and O_2 values of rainbow trout farming using spring water were 12–14.5 °C and 6.5–12 mg/L, respectively. CPRT farming has an annual project production capacity of 350 tonnes (APC). The first-year production amount covering the years 2016–2017 was 260.04 tonnes, the second-year production amount covering the years 2017–2018 was 320.44 tonnes, and the third-year production amount covering the years 2018–2019 was 366.44 tonnes.

2.2. CF (kg CO_2e) analysis of CPRT farming

The study data were obtained from the operating data of the Canlar Alabalık farm. In the design of the CF calculation, CF expended (kg CO_2e kg^{-1}) values were determined according to the total production of the CPRT in three different years. After calculating the CF expended values of the total production in three different years in which different rainbow trout were produced, adaptation was made according to APC. The CF (kg CO_2e) inputs and outputs of CPRT were calculated according to the unit values in Table 2. The proximate composition of Diet-1 and 2 used consisted of 55% crude protein (CP), 14% crude oil (CO), 12% crude ash (CA), 1% crude fiber (CF), 3.900 Mcal ME kg^{-1}; Diet-3 used consisted of 55% CP, 14% CO, 11.8% CA, 0.9% CF, 3.900 Mcal ME kg^{-1}; Diet-4 used consisted of 55% CP, 14% CO, 12.5% CA, 0.9% CF, 3.900 Mcal ME kg^{-1}; Diet-5 and 6 used consisted of 53% CP, 15% CO, 12% CA, 1% CF, 3.800 Mcal ME kg^{-1}; Diet-7 and 8 used consisted of 48% CP, 18% CO, 11.5% CA, 1.2% CF, 4.100 Mcal ME kg^{-1}; Diet-9 used consisted of 46% CP, 19% CO, 10% CA, 1.5% CF, 4.000 Mcal ME kg^{-1}; Diet-10 to 14 used consisted of 45% CP, 20% CO, 9.5% CA, 1.7% CF, 4.000 Mcal ME kg^{-1}; and Diet-15 used consisted of 48% CP, 16% CO, 16.5% CA, 1.6% CF, 3.815 Mcal ME kg^{-1}, respectively. Considering proximate composition information, the diets were formulated according to feed ingredients (according to IAFFD (2020)'s feed ingredients' proximate composition; fish meal, fish oil, soybean meal, wheat grain, wheat byproducts, vitamins, and minerals) provided in the prospectus (Diken & Koknaroglu 2022). The CF expended values of compound diets given in Table 3 were calculated by multiplying the usage rate of feed ingredients (Diken & Koknaroglu 2022) with the unit values of feed ingredients given in the literature (Table 2). CF expended on general management were values that were formed by management practices such as antibiotics, oxygen, chemicals, fuel, electricity, and labor in rainbow trout farming. CF expended on machinery, equipment, and construction was items that ensure the installation and continuity of the enterprise (Table 2). CF expended on transportation was the transportation value calculated by multiplying the transportation distance, the load, and the coefficient (Table 2). All calculations were analyzed with the method in Table 4 in relation to the number of items used

Figure 1 | Location of Canlar Alabalık, Çandır Village Sütçüler-Isparta/Türkiye (Google Earth 2023).

according to the unit values given in Table 2. The CF input and production output per kg fish of the total production of harvested fish rainbow trout were calculated according to the analysis method given in Table 4. CF (kg CO_2e) input for total production, kg harvested fish (), and output for production years are given in Table 5. The one-way ANOVA, followed by Tukey's HSD test, was used to detect the differences between the groups at a significance of 5% (SPSSInc 2015).

3. RESULTS AND DISCUSSION

This study was carried out on a private farm with an annual project production capacity of 350 tonnes APC. Farm production was realized as 74.4, 91.55, and 104.70% of the APC in the first, second, and third years, respectively. The ratio of 122 inland finfish farming facilities with a project capacity of 251–500 tonnes year^{-1}, where almost all of Türkiye's inland finfish production realized by rainbow trout is 25.23% (GDFA 2021). Based on APC value, this private farm is included in this group of assessments based on project capacities.

3.1. CF budget

According to the CF budget or total CF values of CPRT farming in Table 5, the value of APC is determined in Table 6. This value reflects the CF project value for the establishment of CPRT, which is not taken into account in the projects when the farms are established but is likely to be taken into account in the future.

The CF budget distributions of the farm are given in Figure 2. The transportation value of the farm belongs to the compound diet transportation. Data on the diversity of compound diets in the account are given in Table 7, the general management data are given in Table 8, and the distribution in machinery, equipment, and construction diversity are given in Figure 3.

Table 2 | Carbon footprint values for inputs and outputs of the concrete pond rainbow trout farming (CPRT) (kg CO_2e)

Energy content of inputs (Mcal per kg of processed fish as)			
Items	Unit	Mcal unit^{-1}	References
Fish fingerling	kg	1.45	Calculated according to Mehrabi *et al.* (2012)
CF expended on consumed compound diet			
Items	Unit	kg CO_2e unit^{-1}	
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	Hognes *et al.* (2011)
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 and 2	kg	1.08	Calculated
Diet-3	kg	1.08	Calculated
Diet-4	kg	1.08	Calculated
Diet-5 and 6	kg	1.01	Calculated
Diet-7 and 8	kg	0.98	Calculated
Diet-9	kg	0.97	Calculated
Diet-10–14	kg	0.97	Calculated
Diet-15	kg	0.96	Calculated
CF expended on general management			
Antibiotic	kg	2.02	Ecoinvent database v3.4
Vitamin	kg	1.62	Rotz *et al.* (2019)
Oxygen	L	0.2865	Šulc & Ditl (2021)
Commercial product with chloramine-T	kg	0.97	Ecoinvent database v3.4 (Calculated based on ammonia and chlorine values)
Potassium permanganate	kg	1.79	Ecoinvent database v3.4
Hydrogen peroxide	L	1.13	Ecoinvent database v3.4
Formalin, 37% formaldehyde	L	0.267	Ecoinvent database v3.4
Salt	kg	0.0389	Ecoinvent database v3.4
Labor	h	0.70	Nguyen & Hermansen (2012)
Electricity	kWh	0.24	Robertson *et al.* (2015)
Diesel	L	3.11	Robertson *et al.* (2015)
Gasoline	L	2.74	Robertson *et al.* (2015)
CF expended on machinery, equipment, and construction			
Aluminum	kg	8.24	Sabnis *et al.* (2015)
Fiberglass incubation channel	kg	6.42	Calculated (fiberglass, polyester, and galvanized, Hammond *et al.* (2011))
Glass (toughened)	kg	1.27	Hammond *et al.* (2011)
Plastics (PVC)	kg	2.61	Hammond *et al.* (2011)
Timber, softwood (air-dried, dressed)	kg	0.83	Hammond *et al.* (2011)

(*Continued.*)

Table 2 | Continued

Timber, softwood (air-dried, roughsawn)	kg	0.58	Hammond *et al.* (2011)
Timber, softwood (particle board)	kg	0.84	Hammond *et al.* (2011)
Stone	kg	0.056	Sabnis *et al.* (2015)
Concrete	kg	0.117	Sabnis *et al.* (2015)
Cement sand screed	kg	0.145	Hammond *et al.* (2011)
Mortar (normal bricklaying)	kg	0.208	Hammond *et al.* (2011)
Mortar (general plastering)	kg	0.200	Hammond *et al.* (2011)
Limestone	kg	0.032	Hammond *et al.* (2011)
Ceramic (tile)	kg	0.74	Hammond *et al.* (2011)
Brick	kg	0.22	Sabnis *et al.* (2015)
Rebar	kg	1.06	Taffese & Abegaz (2019)
Iron strip	kg	2.09	Pomponi & Moncaster (2018) and Gan *et al.* (2017)
Metal sheets	kg	2.45	Ecoinvent database V3.4
Excavation (0.6 m^3)	h	51.7	Kawai (2011)
Cage net and rope	kg	8.13	Ecoinvent database V3.4
CF expended on transportation			
Truck tonne kg		0.206	Robertson *et al.* (2015)
Energy content of outputs (Mcal per kg of processed fish as)			
Harvested/fresh weight fish		1.93	Calculated according to Welker *et al.* (2018)
Carcass and fillet		1.02 and 0.72	Calculated according to Tatıl (2019)
CF expended per 100 kcal food energy			
Harvested/fresh weight fish		141 kcal per 100 g serving	Calculated according to Fry *et al.* (2018)

Table 3 | Carbon footprint expended value per kg of compound diets (kg CO_2e)

Compound diets	Feed ingredients (FI) CFFI (kg CO_2e kg^{-1})	FM 0.99	FO 0.99	SM 0.541	WG 0.51	WM 0.306	V 1.62	M 1.62	PP 0.13	Diet CF
1 and 2	FI diet (%)	79.78	8.81	1.00	8.91	0.50	0.50	0.50		1.08
	CFFI diet (kg CO_2e kg^{-1})	0.79	0.09	0.01	0.05	0.00	0.01	0.01	0.13	
3	FI diet (%)	80.00	8.78	0.50	9.22	0.50	0.50	0.50		1.08
	CFFI diet (kg CO_2e kg^{-1})	0.79	0.09	0.00	0.05	0.00	0.01	0.01	0.13	
4	FI diet (%)	80.00	8.78	0.50	9.22	0.50	0.50	0.50		1.08
	CFFI diet (kg CO_2e kg^{-1})	0.79	0.09	0.00	0.05	0.00	0.01	0.01	0.13	
5 and 6	FI diet (%)	64.30	9.40	19.80	4.00	1.50	0.50	0.50		1.01
	CFFI diet (kg CO_2e kg^{-1})	0.64	0.09	0.11	0.02	0.00	0.01	0.01	0.13	
7 and 8	FI diet (%)	58.90	12.30	14.50	6.90	6.40	0.50	0.50		0.98
	CFFI diet (kg CO_2e kg^{-1})	0.58	0.12	0.08	0.04	0.02	0.01	0.01	0.13	
9	FI diet (%)	50.47	14.48	23.15	9.23	1.67	0.50	0.50		0.97
	CFFI diet (kg CO_2e kg^{-1})	0.50	0.14	0.13	0.05	0.01	0.01	0.01	0.13	
10–14	FI diet (%)	50.31	15.12	20.54	10.36	2.67	0.50	0.50		0.97
	CFFI diet (kg CO_2e kg^{-1})	0.50	0.15	0.11	0.05	0.01	0.01	0.01	0.13	
15	FI diet (%)	55.50	11.00	19.00	4.00	9.50	0.50	0.50		0.96
	CFFI diet (kg CO_2e kg^{-1})	0.55	0.11	0.10	0.02	0.03	0.01	0.01	0.13	

FM, fish meal, anchovy; FO, fish oil; SM, soybean meal; WG, wheat grain; WM, wheat middlings; V, vitamin; M, mineral; PP, pellets production; CF, carbon footprint expended. The difference is reflected in the calculation due to rounding.

Table 4 | Carbon footprint analysis of concrete pond rainbow trout farming (CPRT)

Carbon footprint budget	
A	CFCD = amount of consumed compound diet (kg) × CF value of compound diet (kg CO_2e kg^{-1}) CFCD: expended on consumed compound diet
B	CFGM = general management item × CF value of each item (kg CO_2e kg^{-1}) CFGM: CF expended on general management
C	CFT = distance (km) and weight (tonne) of transported item × CF value of transportation (kg CO_2e kg^{-1}) CFT: CF expended on transportation
D	CFMEC = machinery, equipment, and construction item × CF value of each item (kg CO_2e kg^{-1}) CFMEC: CF expended on machinery, equipment, and construction
Total CF expended = A + B + C + D	
Carbon footprint expended for outputs	
1	$\text{CF expended for compound diet per day} = \frac{\text{A}}{\text{days on feed}}$
2	$\text{CF expended per kg live weight gain} = \frac{\text{total CF expended}}{\text{live weight gain}}$
3	$\text{CF expended per kg harvested fish} = \frac{\text{total CF expended}}{\text{harvested fish}}$
4	$\text{CF expended per kg carcass or fillet} = \frac{\text{total CF expended}}{\text{harvested fish} \times \text{dressing percentage for carcass or fillet}}$
5	$\text{CF expended per Mcal energy deposited in harvested fish during feeding} = \frac{\text{total CF expended}}{\text{energy deposited in harvested fish or carcass or fillet during feeding}}$
6	$\text{CF expended per Mcal energy deposited in carcass or fillet during feeding} = \frac{\text{total CF expended}}{\text{energy deposited in harvested fish or carcass or fillet during feeding}}$
7	$\text{CF expended per kg of protein deposited in harvested fish during feeding} = \frac{\text{total CF expended}}{\text{total amount of protein accumulated in harvested fish}}$
8	$\text{CF expended per kg of protein deposited in carcass or fillet during feeding} = \frac{\text{total CF expended}}{\text{total amount of protein accumulated in carcass or fillet}}$
9	$\text{CF expended per Mcal of cultural energy expended during production} = \frac{\text{total CF expended}}{\text{total cultural energy expended}}$
10	$\text{Cultural energy expended per Mcal of CF expended during production} = \frac{\text{total cultural energy expended}}{\text{total CF expended}}$
11	$\text{CF expended per 100 kcal food energy in harvested fish (kg } CO_{2e}) = \frac{100 \times \text{total CF expended}}{\text{kcal energy value of total harvested fish}}$

Table 5 | Total carbon footprint expended input and output for production years (CF, kg CO_2e, mean ± SD)

Items		First year (2016–2017) 260.04 t	Second year (2017–2018) 320.44 t	Third year (2018–2019) 366.44 t	Mean ± SD
CF budget	CF expended on consumed compound diet (CFCD)	309.452,48	332.902,55	371.401,94	337.918,99 ± 31.277,9[a]
		1.19	1.04	1.01	1.08 ± 0.10
	CF expended on general management (CFGM)	28.694,08	25.911,92	27.261,79	27.289,27 ± 1.391,29[c]
		0.11	0.08	0.07	0.09 ± 0.02
	CF expended on transportation (CFT)	105.758,85	113.795,38	126.862,52	115.472,25 ± 10.651,30[b]
		0.41	0.36	0.35	0.37 ± 0.03
	CF expended on machinery, equipment, and construction (CFMEC)	74.955,77	74.955,77	74.955,77	74.955,77[b]
		0.29	0.23	0.20	0.24 ± 0.04
	Total CF expended	518.861,19	547.565,62	600.482,02	555.636,28 ± 41.404,61
	*	2.00	1.71	1.64	1.78 ± 0.19
CF expended for outputs	CF expended for compound diet per day	2.161,92	2.262,67	2.450,95	2.291,85 ± 146,71
		0.01	0.01	0.01	0.01 ± 0.00
	CF expended per kg live weight gain	2.00	1.71	1.64	1.78 ± 0.19
	CF expended per kg carcass gained during feeding	2.46	2.11	2.02	2.20 ± 0.23
	CF expended per kg fillet gained during feeding	3.47	2.97	2.85	3.10 ± 0.33
	CF expended per Mcal energy deposited in harvested fish gained during feeding	1.03	0.89	0.85	0.92 ± 0.10
	CF expended per Mcal energy deposited in carcass during feeding	1.96	1.68	1.61	1.75 ± 0.18
	CF expended per Mcal energy deposited in fillet during feeding	2.76	2.37	2.27	2.46 ± 0.26
	CF expended per kg of protein deposited in harvested fish gained during feeding	11.93	10.23	9.81	10.66 ± 1.12
	CF expended per kg of protein deposited in carcass gained during feeding	13.70	11.75	11.26	12.24 ± 1.29
	CF expended per kg of protein deposited in fillet gained during feeding	19.29	16.55	15.87	17.24 ± 1.81
	CF expended per Mcal of cultural energy expended during production	0.36	0.36	0.36	0.36 ± 0.00
	Cultural energy expended per Mcal of CF expended during production	2.74	2.60	2.37	2.57 ± 0.19
	CF expended per 100 kcal food energy in harvested fish (kg CO_2e)	0.1415	0.1212	0.1162	0.1263 ± 0.0134

Σ = one kg harvested/fresh weight/marketed fish, whole body rainbow trout. *CF expended for per kg live weight gain and CF expended for kg harvested fish gained during feeding. t = tonne year^{-1}. CF, carbon footprint. The difference is reflected in the calculation due to rounding. SD, standard deviation, [abc]Means with different superscripts in the same column differ ($P < 0.05$).

3.1.1. Carbon footprint expended on consumed compound diet (CFCD)

CF input for the total production of harvested fish as kg is given in Table 5. First, second, and third years, and average CFCD values per kg of harvested fish were 1.19, 1.04, 1.01, and 1.08 kg CO_2e, respectively (Table 5). According to the three-year CFCD values, when the farm is reared with an APC, the CFCD value will be 1.02 kg CO_2e (Table 6). Cage rainbow trout farming in the same basin has a lower CFCD mean of 0.82 kg CO_2e values (Diken *et al.* 2022; Table 9). CF shares of diets in CFCD are given in Figure 2. It has been determined that CFCD constituted 59.64, 60.80, 61.85, and 60.76% of the total kg CO_2e expended for the first, second, and third years, and average, respectively. Because of the high values of emissions associated with fishmeal with high protein values and emissions due to land-use change (soybean production), feed emissions were high in salmonids (MacLeod *et al.* 2020). An increase in the CFCD was observed due to increased feed consumption as the fish grew. The CFCD ratio of the 3, 4, 5, and 6 mm compound diets of the growing-out period was calculated as 90.90% ($P < 0.05$) (Table 7). It has been stated that there is a relationship between CF analysis and energy calculations (Flos & Reig 2017). With this expression, a similar relationship was found between the 73.69% of the cultural energy expended on consumed compound diet share of CPRT in the cultural energy budget (Diken & Koknaroglu 2022) and the 60.76% of the CFCD share in CPRT was calculated in this study. Eighty-five per cent of the total CF feed share in caged salmon production reported by Ziegler *et al.* (2020) and 73.69% of the CFCD share in cage rainbow trout reported by Diken *et al.* (2022) and 60.72% of the CFCD shares in CPRT in this study reveal the differences in the production systems of aquaculture (Table 9).

The increase in production caused an increase in CFCD and total CF as it would also increase feed consumption due to feed conversion rate (FCR), which was also stated by Ziegler *et al.* (2020). Adhikari *et al.* (2013) reported that feed constitutes 90% of the CF in different aquaculture culture systems in India. Although this result is above the CPRT's CF value, it reveals the necessity of studying the CF values of species (species-specific) and culture system (culture-specific) differences in

Table 6 | Total carbon footprint expended input and output of the projected annual production capacity of 350 tonnes (APC) according to the linear regression equation (CF, kg CO_2e)

Items		The linear regression equation	kg CO_2e
CF budget	CF expended on consumed compound diet	$y = -0.0017x + 1.6179$ ($R^2 = 0.9056$)	1.02
	CF expended on general management	$y = -0.0003x + 0.1978$ ($R^2 = 0.9256$)	0.09
	CF expended on transportation	$y = -0.0006x + 0.5534$ ($R^2 = 0.9077$)	0.34
	CF expended on machinery, equipment, and construction	$y = -0.0008x + 0.4923$ ($R^2 = 0.9915$)	0.21
	Total CF expended	$y = -0.0034x + 2.8614$ ($R^2 = 0.9344$)	1.67
	CF expended on consumed compound diet	$y = 0.0207x + 54.233$ ($R^2 = 0.9974$)	61.48%
	CF expended on general management	$y = -0.0095x + 7.9344$ ($R^2 = 0.9331$)	4.61%
	CF expended on transportation	$y = 0.007x + 18.563$ ($R^2 = 0.9987$)	21.01%
	CF expended on machinery, equipment, and construction	$y = -0.0182x + 19.269$ ($R^2 = 0.9569$)	12.90%
CF expended for outputs	CF expended per kg live weight gain	$y = -0.0034x + 2.8614$ ($R^2 = 0.9344$)	1.67
	CF expended for kg carcass gained during feeding	$y = -0.0042x + 3.521$ ($R^2 = 0.9352$)	2.05
	CF expended for kg fillet gained during feeding	$y = -0.0059x + 4.96$ ($R^2 = 0.9352$)	2.90
	CF expended per Mcal energy deposited in harvested fish gained during feeding	$y = -0.0018x + 1.4781$ ($R^2 = 0.9352$)	0.85
	CF expended per Mcal energy deposited in carcass during feeding	$y = -0.0033x + 2.8036$ ($R^2 = 0.9352$)	1.65
	CF expended per Mcal energy deposited in fillet during feeding	$y = -0.0047x + 3.9494$ ($R^2 = 0.9352$)	2.30
	CF expended per kg of protein deposited in harvested fish gained during feeding	$y = -0.0203x + 17.078$ ($R^2 = 0.9352$)	9.97
	CF expended per kg of protein deposited in carcass gained during feeding	$y = -0.0233x + 19.605$ ($R^2 = 0.9352$)	11.45
	CF expended per kg of protein deposited in fillet gained during feeding	$y = -0.0329x + 27.617$ ($R^2 = 0.9352$)	16.10
	Cultural energy expended per Mcal of CF expended during production	$y = -0.0034x + 3.6557$ ($R^2 = 0.9569$)	2.47
	CF expended of calories deposited in harvested fish gained during feeding	$y = -0.0002428x + 0.2029332$ ($R^2 = 0.9344$)	0.1173 kg CO_2e/100 kcal

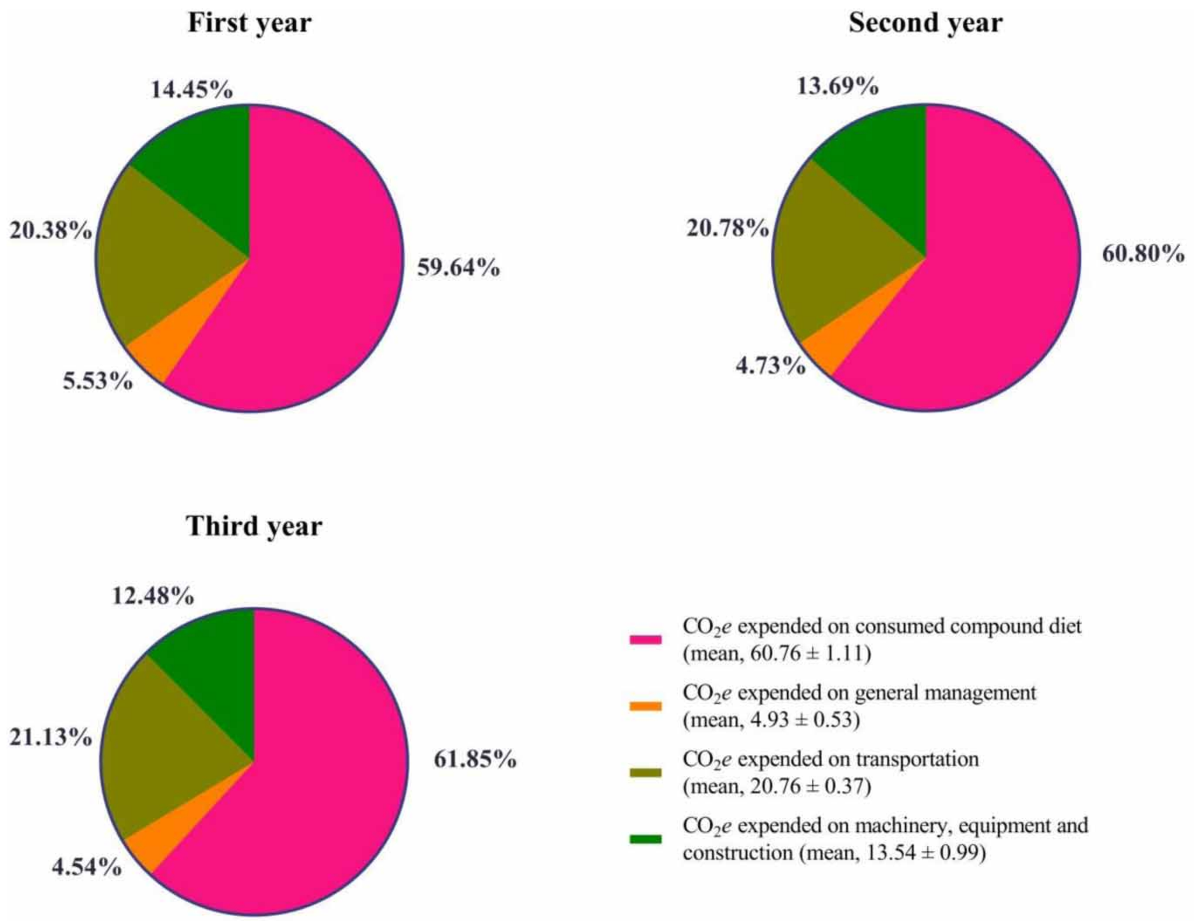


Figure 2 | Carbon footprint (kg CO_2e) expended shares the total carbon footprint (kg CO_2e) expended according to the three-year values (%).

aquaculture on a national and global scale. Depending on the feed ingredients of the trout feed, the climate change potential (kg CO_2e) of the plant-based low fisheries diet was 6% lower than the fishmeal-based standard diet (Boissy *et al.* 2011). This situation reveals that the CF of feed formulations can be improved in trout farming. da Silva Pires *et al.* (2022) reported that strategies reducing the influence of gathering individual feed ingredients from different production systems and distances to make the final feed on the environmental impact is preferred in the LCA analysis of aquaculture. This would also be reflected in the lesser global warming effect of aquafeeds. This is consistent with the statement that a high impact of CFCD on the sustainability of CPRT rearing systems was the case in the present study.

3.1.2. Carbon footprint expended on general management (CFGM)

First, second, and third years, and average CFGM values per kg of harvested fish were 0.11, 0.08, 0.07, and 0.09 kg CO_2e, respectively (Table 5). According to the three-year CFGM values, when the farm is reared with an APC, the CFGM value will be 0.09 kg CO_2e (Table 6). This value was determined between 0.11 and 0.19 kg CO_2e in cage rainbow trout farming (Diken *et al.* 2022; Table 9). The shares of CFGM in the total kg CO_2e expended were calculated in the first, second, and third years, and the average was 5.53, 4.73, 4.54, and 4.93%, respectively (Figure 2). Labor had an average share of 46.64% in CFGM and an average share of 2.30% in total CO_2e expended ($P < 0.05$) (Table 8). The shares of diesel and electricity in CFGM were calculated as 33.14 and 12.65%, respectively ($P < 0.05$). The shares of these three items in total CO_2e expended were determined as approximately 1.63% diesel and 0.62% electricity, respectively (Table 8).

3.1.3. Carbon footprint expended on transportation (CFT)

Since fish farming is an integrated facility from egg to harvested fish, transportation only includes the value at which the compound diet is transported. Depending on the annual production amount, due to the increased feed consumption, also the total

Table 7 | Carbon footprint expended distribution of diets in carbon footprint expended on consumed compound diet (CFCD) (kg CO_2e, mean ± SD)

Compound diets	Carbon footprint (kg CO_2e) expended	%
Diet-1 (150–300 µ)	80.67 ± 38.03[d]	0.02 ± 0.01
Diet-2 (Granular-1; 300–500 µ)	430.25 ± 53.78[d]	0.12 ± 0.02
Diet-3 (Granular-2; 500–800 µ)	566.53 ± 65.65[d]	0.16 ± 0.02
Diet-4 (Granular-3; 800–1,200 µ)	898.78 ± 105.53[d]	0.26 ± 0.03
Diet-5 (1 mm)	2.435,85 ± 145.48[d]	0.72 ± 0.09
Diet-6 (1.5 mm)	3.712,57 ± 162.00[d]	1.09 ± 0.13
Diet-7 (2 mm)	8.694,64 ± 284.14[d]	2.58 ± 0.29
Diet-8 (2.5 mm)	4.347,32 ± 512.25[d]	1.29 ± 0.21
Diet-9 (3 mm)	71.852,81 ± 8.106,64[b]	21.27 ± 1.07
Diet-10 (4 mm)	56.354,94 ± 13.944,23[c]	16.55 ± 2.62
Diet-11 (5 mm)	82.278,21 ± 4.383,02[ab]	24.43 ± 1.23
Diet-12 (6 mm)	96.608,46 ± 8.366,54[a]	28.65 ± 1.63
Σ (Diet-9/3 mm, Diet-10/4 mm, Diet-11/5 mm, Diet-12/6 mm)		90.90 ± 1.02
Diet-13 (8 mm)	4.347,38 ± 483.04[d]	1.29 ± 0.14
Diet-14 (10 mm)	4.492,29 ± 846.36[d]	1.32 ± 0.13
Diet-15 (10 mm)	845.18 ± 120.40[d]	0.25 ± 0.01

The difference is reflected in the calculation due to rounding. SD, standard deviation, [abcd]Means with different superscripts in the same column differ ($P < 0.05$).

Table 8 | Contribution of each item to carbon footprint expended on the general management (CFGM) (kg CO_2e, mean ± SD)

Items	Carbon footprint expended (kg CO_2e)	%
Labor	12.705,00[a]	46.64 ± 2.38
Diesel	9.081,20 ± 1.613,61[b]	33.14 ± 4.22
Electricity	3.434,69 ± 578.23[c]	12.65 ± 2.47
Gasoline	799.17 ± 259.34[d]	2.90 ± 0.80
Antibiotic	201.66 ± 1.17[d]	0.74 ± 0.04
Vitamin	178.74 ± 15.40[d]	0.66 ± 0.08
Oxygen	14.80 ± 7.07[d]	0.05 ± 0.02
Formalin, 37% formaldehyde	494.93 ± 49.32[d]	1.82 ± 0.27
Potassium permanganate	232.10 ± 12.79[d]	0.85 ± 0.08
Hydrogen peroxide	69.68 ± 14.22[d]	0.26 ± 0.07
Commercial product with chloramine-T	77.27 ± 13.63[d]	0.28 ± 0.06
Salt	0.02 ± 0.00[d]	0.00 ± 0.00

The difference is reflected in the calculation due to rounding. SD, standard deviation, [abcd]Means with different superscripts in the same column differ ($P < 0.05$).

CFT increased. The total CFT value in the second and third years increased by 7.60 and 11.48%, respectively, compared with the previous year. On the other hand, production increased by 23.23 and 14.36, respectively. First, second, and third years, and their average CFT values per kg of harvested fish were 0.41, 0.36, 0.35, and 0.37 kg CO_2e, respectively (Table 5). The shares of CFT in the total kg CO_2e expended were calculated in the first, second, and third years and the average was 20.38, 20.78, 21.13, and 20.76%, respectively (Figure 2). Since the percent change in the total CFT value remained lower than the percent change in the production change value, the CFT value per kg decreased over the years. According to the three-year CFT values, when the farm is reared with an APC, the CFT value will be 0.34 kg CO_2e (Table 6). This value was determined between 0.01 and 0.06 kg CO_2e in cage rainbow trout farming (Diken *et al.* 2022; Table 9). Here, attention

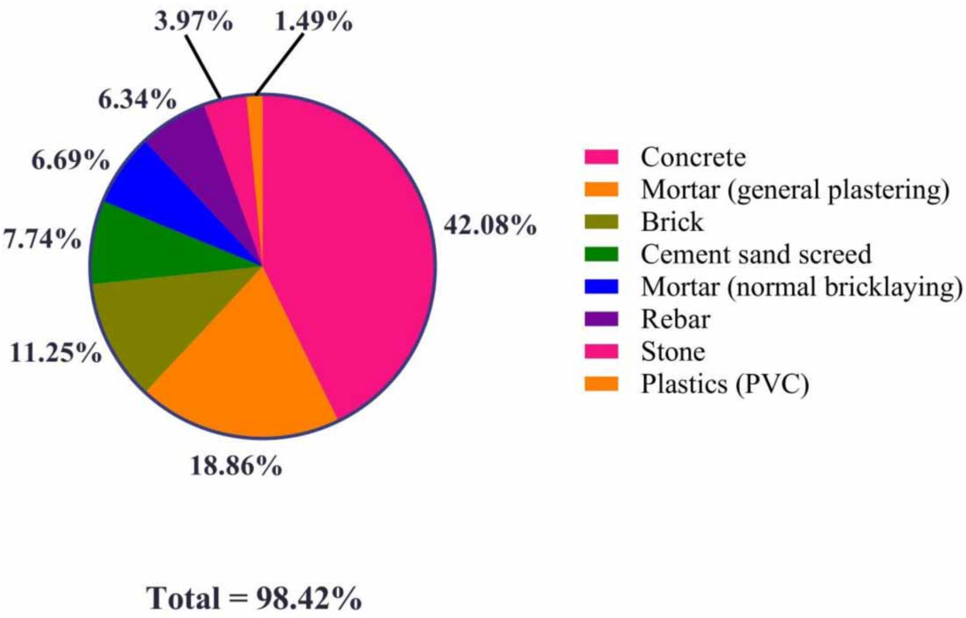


Figure 3 | Share of items kg CO_2e expended on machinery, equipment, and construction items (%) (total share of concrete, mortar-general plastering, brick, cement sand screed, mortar-normal bricklaying, rebar, stone, and plastics-PVC was 98.42%, and given in Table 2 another item total, which was less than 1%, was 1.58%).

should be paid to the transportation differences between the two fish farmings (Diken *et al.* 2022). Similarly, it is reported that the consumed compound diets and compound diets transportation depending on the FCR values of rainbow trout farms produced in Karacaören-I Dam Lake in the same basin caused an increase in CF values of the basin (Diken 2022).

The recent reports highlight the importance of reduction of distances between feed production and usage sites, employment of feed production facilities in aquaculture sites, and selection of locally available feed ingredients in diet formulations to reduce transportation emission or preference for low-carbon emission feedstuffs in diets to reduce the environmental impact of aquaculture (HatcheryFeedManagement 2021; HatcheryInternationalStaff 2021; da Silva Pires *et al.* 2022). Likewise, our results support the need to decrease CFCD and CFT associated with diet and transport in CPRT farming systems.

3.1.4. Carbon footprint expended on machinery, equipment, and construction (CFMEC)

Since machinery, equipment, and construction were fixed items, the total value of CFMEC has been calculated at the same value for three years (Table 5). However, it was determined that the kg value of the harvested fish decreased depending on the production amount. The production of the first, second, and third years and their average were calculated as 0.29, 0.23, 0.20, and 0.24, respectively. According to the three-year CFMEC values, when the farm is reared with an APC, the CFMEC value will be 0.21 kg CO_2e (Table 6). The shares of CFMEC in the total kg CO_2e expended were calculated as the first, second, and third years and the average was 14.45, 13.69, 12.48, and 13.54%, respectively (Figure 2). This value was determined between 0.09 and 0.16 kg CO_2e in cage rainbow trout farming (Diken *et al.* 2022; Table 9). Concrete constitutes 42.08% of CFMEC (Figure 3). According to the average CFMEC share is 13.54% as given in Figure 2, the share of concrete in the total CF expended is 6.50%. According to the average total CF expended value, it can be stated that the CF expended value of the concrete in the production of per kg rainbow trout was 0.12 kg CO_2e (Table 5; Figures 2 and 3).

3.1.5. Total carbon footprint expended

The kg value of total CO_2e expended can also be used as CO_2e expended per kg live weight gain and CO_2e expended per kg harvested fish. The increase in production has increased the CF budget, that is, the total amount of CF. However, the total kg CO_2e value decreased. The kg CO_2e value against the annual tonne production of the first, second, and third years was calculated as 260.04 vs 2.00, 320.44 vs 1.71, and 366.44 vs 1.64, respectively (Table 5).

Table 9 | Discussion of study results with reference publications (CF, kg CO_2e kg^{-1})

Rainbow trout farmed in concrete ponds (CPRT)				
CF expended on consumed compound diet (CFCD)				
First	Second	Third	Mean	APC
1.19 kg CO_2e; 59.64%	1.04 kg CO_2e; 60.85%	1.01 kg CO_2e; 61.48%	1.08 kg CO_2e; 60.76%	1.02 kg CO_2e; 61.85%
Referenced citations				
mean 0.82 kg CO_2e and 73.69% cage RT (Diken *et al.* 2022) and 73.69% salmon cage (Ziegler *et al.* 2020)				
CF expended on general management (CFGM)				
0.11 kg CO_2e; 5.53%	0.08 kg CO_2e; 4.73%	0.07 kg CO_2e; 4.54%	0.09 kg CO_2e; 4.93%	0.09 kg CO_2e; 4.61%
Referenced citation				
mean 0.16 kg CO_2e and 13.08% cage RT (Diken *et al.* 2022)				
CF expended on transportation (CFT)				
0.41 kg CO_2e; 20.38%	0.36 kg CO_2e; 20.78%	0.35 kg CO_2e; 21.13%	0.37 kg CO_2e; 20.76%	0.34 kg CO_2e; 21.01%
Referenced citation				
mean 0.03 and 2.52% cage RT (Diken *et al.* 2022)				
CF expended on machinery, equipment, and construction (CFMEC)				
0.29 kg CO_2e; 14.45%	0.23 kg CO_2e; 13.69%	0.20 kg CO_2e; 12.48%	0.24 kg CO_2e; 13.54%	0.21 kg CO_2e; 12.90%
mean 0.13 kg CO_2e and 10.71% cage RT (Diken *et al.* 2022)				
Total CF expended				
2.00	1.71	1.64	1.78	1.67
Referenced citations				
General	1.8–3.3 kg CO_2e (FEAP 2022) and 3.27 kg CO_2e (MacLeod *et al.* 2020) and 2–7 kg CO_2e (Boyd 2013) and 3–15 kg CO_2e (Nijdam *et al.* 2012)			
Freshwater fish	3.47 kg CO_2e (MacLeod *et al.* 2020)			
Marine fish	5.18 kg CO_2e (MacLeod *et al.* 2020)			
Rainbow trout	1.13 kg CO_2e cage (Diken *et al.* 2022) and 2.75 kg CO_2e flow-through (Aubin *et al.* 2009) and different systems 250–300 g 1.76–1.85 kg CO_2e, 900–1,500 g 1.96–2.29 kg CO_2e, and 2,000–3,000 g 2.43–2.76 kg CO_2e (Papatryphon *et al.* 2004)			
Salmonids	3.17 kg CO_2e (MacLeod *et al.* 2020)			
Atlantic salmon	2.9 kg CO_2e (MH 2017) and 7.01 kg CO_2e RAS and 3.39 kg CO_2e cage (Liu *et al.* 2016) and 2.16 kg CO_2e (Pelletier *et al.* 2009) and 1.90–2.77 kg CO_2e different systems (Ayer & Tyedmers 2009) and 1.2–2.7 kg CO_2e (Pelletier & Tyedmers 2007)			
Cyrinids	3.25 kg CO_2e (MacLeod *et al.* 2020)			
Indian carp	2.92 kg CO_2e (MacLeod *et al.* 2020) and 1.84 (Robb *et al.* 2017)			
Pangasisus	5.91 kg CO_2e big farm, 6.73 kg CO_2e small farm (Robb *et al.* 2017)			
Catfish	3.05 kg CO_2e catfish (MacLeod *et al.* 2020) and 1.37 striped catfish culture (Robb *et al.* 2017)			
Tilapia	3.70 kg CO_2e (MacLeod *et al.* 2020) and 5 kg CO_2e RAS (Hagos 2012) and 1.58 kg CO_2e Nile tilapia (Robb *et al.* 2017) and 2.10 kg CO_2e Indonesian tilapia (Pelletier & Tyedmers 2010)			
Cobia	8 kg CO_2e cage (Hagos 2012)			

RT, rainbow trout.

According to many reports, aquaculture is the most efficient-food animal protein producer compared with other farm animals' production (Table 1). In this report, it is determined as 1.8–3.3, 3.27, 2–7, and 3–15 kg CO_2 per kg of edible products. The values showed that CF expended per kg harvested fish decreases depending on the annual production capacity and the values that should be made according to the APC are also lower than the values in these reports. The CF of CPRT is much lower than the overall CF values in the MacLeod *et al.* (2020) report on world freshwater and marine fish farming given in Table 9. Therefore, microdata of aquaculture such as CPRT will make an important contribution to national and global interpretations.

The kg CO_2e CF value of rainbow trout harvested at approximately the same market size was found to be high in CPRT compared with inland water cage aquaculture (Diken *et al.* 2022; Table 9). Similarly, the value of 1.67 kg CO_2e year^{-1} of CPRT CF expended, adapted to the APC, is higher than the value of cage rainbow trout reared in inland waters (Diken *et al.* 2022; Table 9). The CF values of Turkish CPRT are similar to the CF values of portion size (250–300 g) of rainbow trout farmed in France (Papatryphon *et al.* 2004). However, it is lower than the CF of flow-through rainbow trout farming in the same country (Aubin *et al.* 2009; Table 9). Rainbow trout have CF values according to the principle differences and different farming techniques (Table 9).

The CF value of CPRT is lower than that of 2.16 kg CO_2e Atlantic salmon farming given in the Pelletier *et al.* (2009) report (Table 9). Ayer & Tyedmers (2009) and Pelletier & Tyedmers (2007) reported a 1.9–2.77 and 1.2–2.7 kg CO_2e value per kg live weight gain of cultured Atlantic salmon, which is similar to our study results. This result is similar to the fact that the salmon CF value produced in land-based closed containment water recirculating aquaculture systems is higher than that of open net-pen systems (Liu *et al.* 2016). However, the CF values of the rainbow trout rearing in the inland waters of Türkiye were lower than those of RAS and open-cage Atlantic salmon (Liu *et al.* 2016; Diken *et al.* 2022; Table 9).

In the life cycle analysis of fish farming systems, Hagos (2012) found that the CF of the cobia cage farm is higher than that of the Asian sea bass recirculation farm. Hagos (2012) calculated these values as 8 kg CO_2e kg^{-1} fish output for cobia cage farm CF and 1.7 kg CO_2e kg^{-1} fish output for Asian sea bass recirculation farm CF (Table 9). On the other hand, the 1.64–2.00 (1.67, APC) kg CO_2e CF value given in Table 5 was similar to the striped catfish culture system, while the values of carp culture and Nile tilapia (Robb *et al.* 2017) were higher than the composite fish culture, shrimp culture, seabass (Srinivasa Rao *et al.* 2016), and shrimp in the pond (Kauffman *et al.* 2018). Moreover, da Silva Pires *et al.* (2022) emphasized that the climate warming potential of aquaculture operations in terms of kg CO_2e is greatly influenced by the selected aquaculture methods and species. The reason for this depends on the species and aquaculture system differences of aquaculture. Cultivation of rainbow trout, a carnivorous species, in intensive concrete ponds reveals species and system differences.

Besides being the primary producer of macroalgae, the bivalves are fed with natural foods, so there are no feed emissions and therefore their CF is low (MacLeod *et al.* 2020; Jones *et al.* 2022). The CF budgets of such types consist of logistics resources based on investment and transportation. Freshwater fish such as carp, catfish, and tilapia are omnivorous or herbivorous and require low levels of protein and fish meal due to their nutritional characteristics, and breed easily, and are tolerant to oxygen and nutrient wastes, and are farmed with low-cost technologies (MacLeod *et al.* 2020). Therefore, the CF, and the effects of climate change, may be low (Table 9). On the other hand, the most important factors in CF calculations are the CF of compound diets, which consists of nutritional needs based on species differences and feed ingredients, and the CF of feed consumption based on FCR (Henriksson *et al.* 2015; Diken 2022; Diken *et al.* 2022). Therefore, for the sustainability of aquaculture, feed safety based on feed ingredients is needed (Hognes *et al.* 2011; D'Abramo 2021). On the other hand, transportation and system differences that reveal the budget value of the investment and CF values of energy resources based on the aquaculture system, as well as the project capacity and the changing production amount of the project capacity over the years affect these calculations (Henriksson *et al.* 2015; Diken 2022; Diken *et al.* 2022). In these calculations, intensive production generally has a lower CF as it increases production efficiency (Lutz 2021). As in the results of the study, the decrease in CF values due to the increased production capacity is similar to the fact that the product obtained from rice-fish symbiosis systems has higher carbon emissions in small farms compared with large farms (Cui *et al.* 2020), and the CF of pangasius farming compared with large farms. The fact that it is higher in small-scale family companies (Henriksson *et al.* 2015) reveals the decreasing CF value in production due to increased production capacity.

As a result, the differences in the rearing systems are the main reasons for the similarities and differences between the CF results of rainbow trout and Atlantic salmon rearing (Table 9). If the use of feed ingredients based on similar carnivorous rations of these two species is ignored, the production of machinery and equipment used in land-based facilities and marine systems, and the structural value differences cause the difference in kg CO_2e unit values, thus affecting the climate potentials of the facilities. As a result, in addition to the CF-based climate identities of rainbow trout and salmon species in the same family, the CF differences of species belonging to other families reveal the necessity of climatic identity species definitions based on the aquaculture system.

The inability of fish and crustacean species to produce CH_4 through enteric fermentation, their direct secretion of ammonia, high reproductive ability and low FCR values, less energy requirement for locomotion, and cold-blooded vertebrates indicate that aquaculture species have a lower emission than ruminant monogastric species such as pigs and chickens (MacLeod *et al.* 2020). Additionally, globally, aquaculture has a much lower energy density than ruminant meat, while it has similar proportions to the main monogastric commodities (pig and broiler meat) (MacLeod *et al.* 2020). The CF expended for harvested fish was lower than for sheep, cattle, cows, pork/pig, poultry, and buffalo (Nemry *et al.* 2001; Rotz *et al.* 2010, 2019; MacLeod *et al.* 2020; Table 1). In addition, the effects of climate change on sectorial growth in ensuring food security of the aquaculture sector (Cubillo *et al.* 2021) have become an inevitable reality that will affect the CF of aquaculture. Reducing energy in feed production in aquaculture, improving FCR, increasing the variety of feed ingredients used, selecting species with high portion sizes, considering FCR, and practices that increase production efficiency will reduce CF values together with energy savings (Flos & Reig 2017).

3.2. CF for outputs

3.2.1. CF expended per kg carcass and fillet gained during feeding

The average CF expended for kg carcass and fillet gained during feeding 2.20 and 3.10 kg CO_2e CF values, respectively in given Table 5 were similar to the 2–7 kg CO_2e kg^{-1} meat CF of the aquacultured fish reported by Boyd (2013). The emission intensity of 2–4 kg (kg CO_2e/carcass weight) of salmon aquaculture in the European region is more similar to the Eastern Europe emission intensity of 2.05 CF expended per kg marketed carcass value adapted to the project capacity of our study (MacLeod *et al.* 2020). Considering the regression analysis of these three-year production (TYP) values, the CF expended for kg carcass and fillet gained during feeding value of the APC was determined as 2.05 and 2.90 kg CO_2e, respectively (Table 6). On the other hand, it was higher than the kg CO_2e value of cage rainbow trout farming (Diken *et al.* 2022). It was determined that CF expended for kg carcass gained during feeding of CPRT was higher than cage rainbow trout farming. However, the ratio of the CF expended per kg marketed carcass to the CF expended per kg marketed fillet for cage rainbow trout farming and CPRT was similarly around 41% (Diken *et al.* 2022). The reason for this is the dressing percentage for carcass and fillet (81% vs 57.5%). The CF value of the total CF expended budget per kg of harvested fish, compared with the carcass and fillet ratios, increased by 23.4 and 73.8%, respectively (1.78 vs 2.20 vs 3.10).

3.2.2. CF expended per Mcal energy deposited in harvested fish gained, carcass, and fillet during feeding

The average CF expended per Mcal energy deposited in harvested fish gained during feeding was 0.92 kg CO_2e (Table 5). These values increased by 89.7% and 167.2 compared with the carcass and fillet ratio of the harvested fish (0.92 vs 1.75 vs 2.46). Considering the regression analysis of these TYP values, the CF expended per Mcal energy deposited in harvested fish, carcass, and fillet gained during feeding value of the APC was determined as 0.85, 1.65, and 2.30 kg CO_2e, respectively (Table 6).

3.2.3. CF expended per kg of protein deposited in harvested fish, carcass, and fillet gained during feeding

The average CF expended per kg of protein deposited in harvested fish gained during feeding was 10.66 kg CO_2e (Table 5). These values increased by 14.8 and 61.7% compared with the carcass and fillet ratio of the harvested fish (10.66 vs 12.24 vs 17.24). Considering the regression analysis of these TYP values, the CF expended per kg of protein deposited in harvested fish, carcass, and fillet gained during feeding value of the APC was determined as 9.97, 11.45, and 16.10 kg CO_2e, respectively (Table 6). While the protein increase rates of the CF were similar to the cage rainbow trout results (Diken *et al.* 2022), the energy increase rates were found to be low. This was because the total energy value of fingerlings stocked in cage farming is deducted from the total energy value of the harvested fish. The high protein retention efficiency for harvested fish, carcasses, and fillets in rainbow trout farming can be explained by the fact that rainbow trout is a good converter of feed protein to edible meat protein (Diken & Koknaroglu 2022; Diken *et al.* 2022). At the same time, since salmon produces twice as much protein as beef (MH 2017), the recovery of carcass and fillet waste products will support the sustainability of the blue economy in terms of CF.

3.2.4. CF expended per Mcal of cultural energy expended during production and cultural energy expended per Mcal of CF footprint expended during production

The average CF expended per Mcal of cultural energy expended during production was calculated as 0.36 kg CO_2e (Table 5). In other words, kg CO_2e was calculated for each 2.57 Mcal cultural energy expended during the production period. Considering the regression analysis of these TYP values, cultural energy expended per Mcal of CF expended during the production value of the APC was determined as 2.47 (Table 6). In cage rainbow trout farming, these values were determined as the average CF value of 0.35 kg CO_2e per Mcal of cultural energy consumed during production and kg CO_2e expended value for each 2.86 Mcal cultural energy expended during the production period, respectively (Diken *et al.* 2022). According to this evaluation which shows the relationship between carbon emission and cultural energy use depending on external energy (fossil fuel) input (Diken *et al.* 2022), it can be stated that rainbow trout cage farming was more sustainable than CPRT.

3.2.5. CF expended per 100 kcal food energy in harvested fish (kg CO_2e)

The first, second, and third years and averages of our study indicate that the CF expended per 100 kcal food energy in harvested fish were 0.1415, 0.1212, 0.1162, and 0.1263 kg CO_2e, respectively (Table 5). Considering the regression analysis of these TYP values, CF expended per 100 kcal food energy in harvested fish value of the APC was determined as 0.1173 (Table 6). Chang *et al.* (2017)'s CF analysis was the result of the shrimp farm life cycle assessment, while this study was the CF value per Mcal of cultural energy expended during production. When the kg CO_2e kg^{-1} meat CF of the aquacultured fish and other farm animals as described in the report by Boyd (2013), and the carbon emissions related to producing various foods (kg CO_2/100 kcal) as described in the report by Chang *et al.* (2017) were examined; the status of aquaculture is correlated with the results of our analysis of total CO_2e expended (CF for per kg live weight gain or CF expended for per kg harvested fish) and CF expended per 100 kcal food energy in harvested fish. When the protein and calorie retention rates of aquatic and farm animals species by Fry *et al.* (2018) and the carbon emissions (kg CO_2/100 kcal) associated with food production reported by Chang *et al.* (2017) were compared; it is seen that the species with high protein and calorie retention rates have low carbon emissions. When these reports (Chang *et al.* 2017; Fry *et al.* 2018; Boyd *et al.* 2020) and the results of the present study for the total CF expended, CF expended per Mcal of cultural energy expended during production, and CF expended per 100 kcal food energy in harvested fish were taken together, CPRT farming can be considered as sustainable production. In terms of the effects of climate change on sectorial growth in ensuring food safety in the aquaculture industry (Cubillo *et al.* 2021), it has become an inevitable reality that aquaculture will affect the CF.

In addition to the results given in the carbon budget, it is extremely important to determine the effects on food security based on the global climate crisis. I can recommend that this should be handled in two ways. Sustainable protein safety based on the climate identities of the crop, animal, and aquaculture production should be determined and discussed globally. It will determine the roadmaps in which these countries' agricultural, animal and aquatic products will turn into policies and targets that will support their positive contributions to the world ecosystem. Secondly, the critical lines of the species within these production areas and the breeding systems of these species, namely the threshold lines, should be determined, regardless of which production areas of agricultural, animal, and aquatic products they have in the global sense. The establishment of a taxation system based on this will reach a level where sustainable food production will contribute to the sustainable world ecosystem. For example, after determining the threshold lines of food production of different aquaculture systems such as RAS, cage, and open-cage of rainbow trout, tax reductions should come for businesses with production values below the threshold line of this species' rearing system with follow-up warning models. The climate identity labeling of the products should be handled within this framework. As a result, using less buried carbon resources will contribute to a sustainable world by reducing the pressures on the world's ecosystems and positively affecting the effects of the climate crisis. All these positive ethics also include attributes that are adaptive to the low CF circular economy definitions of aquaculture, which are very prone to circular economy models in which all the products obtained and product wastes are used.

4. CONCLUSION

Due to the decrease in the carbon footprint expended (CF, CO_2e) value of the product obtained as a result of the increase in the production capacity in CPRT farming, the potential global warming impact has been reduced due to the reduction in fossil fuel use per product. In this case, production with the project capacity will positively affect climate change. In aquaculture farm management, it is important to obtain products with a high survival rate without wasting resources, for the protein value with low CF value in meeting the global food protein demand. In this respect, software programs such as Aqua Manager, which determine the CF values of the product obtained, should be evaluated within the farm management. Due to the effects of global warming and climate change, CF label values should become a necessity in the marketability of products globally and taxations based on CF values should also be regulated. In our world evolving toward a new order, this approach offers expansions to the paradigm of society 5.0 (effects of industrial nutrition) and industry 5.0 (artificial intelligence and software in terms of products, raw materials, and feed ingredients).

The results show that rainbow trout has a very important place in CF expended based on compound diet and compound diet. Therefore, in rainbow trout farming, alternative feed ingredients that do not affect the physiological development and FCR values of the rainbow trout and have low CF values (kg CO_2e) should be emphasized. This analysis method, in which the direct and indirect effects of production steps in a farm are determined and monitored, shows that the CF values of the species (species-specific) and culture system (culture-specific) differences of aquaculture can be revealed on a national and global scale. The projections of sustainable food production should be presented by comparing the CF of fisheries species and aquaculture systems with the protein values of animal origin. With this approach, the results revealed that one of the carnivorous species, rainbow trout farming in concrete ponds is a sustainable industry. In line with the increasing food demands of aquaculture specific to the species and culture system due to anthropogenic climate change and global population growth, studies on the '*sustainability of the blue economy*' that reveal the results of global food security are recommended.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

ETHICS APPROVAL

In this study, animals were not used.

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