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The need for innovations to secure the future of artisanal mussel farming in the coastal sea of the Gulf of Trieste (Slovenia)

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ABSTRACT

Mariculture along the Slovene coastline is mainly mussel culture operated as a family business; in one case, it is combined with sea bass farming. It started in the early 70 s with cultivation of Mediterranean mussels, while today, the two largest producers incorporate the cultivation of Venus clams and oysters as species with higher economic value on the market. Currently, all mussels and clams produced in Slovenia are sold in the Slovenian, Italian, Croatian and French markets. The production of Mediterranean mussels (*Mytilus galloprovincialis*) has increased steadily, with the main obstacles being a limited area for cultivation, occasional harmful algal blooms, predation by gilthead seabream and flatworms. In addition, more recent summer heatwaves negatively affected mussel production when seawater reached high temperatures at the thermal limits unsuitable for mussel growth. This study aimed to collect first-hand information about the current mussel production technology, processes and needs to identify opportunities for innovations that could benefit the entire sector (increased knowledge, production yield, reduced workload and effort with administrative issues). The study was based on a semi-structured questionnaire with the owners of mussel farms. Analysis of the questionnaire was supplemented with current knowledge from the field and provided comprehensive insight into a small sector of mussel farming along the Slovenian coast and its possible development in the future.

1. Introduction

World mussel aquaculture is an important sector that has been continuously growing since the 1950s. It is responsible for 94% of world mussel production and was recognised as an important sector contributing to food safety in the European Union (FAO, 2020). China contributes 43% of the world's mussel production, followed by the European Union (EU), which contributes about 20%. Production of European mussel aquaculture, which refers to mytiliid species (*Mytillus edulis, M. trossulus* and *M. galloprovincialis*), has decreased since the 1990s (600,000 t to 480,000 t in 2016). The decline in mussel production in the EU gained broad interest and was recently analysed through a SWOT analysis of stakeholders to highlight causes, weaknesses, and strengths in the sector (Avdelas et al., 2021). The aquaculture sector, in general, was fast growing in the recent decades, also called the Blue Revolution, receiving substantial subsidies for infrastructure and innovations. Analysis of subsidies in aquaculture pointed out that financial support failed to stimulate the sector's growth in the EU (Guillen et al., 2019).

Slovenia was among the EU countries that reported data on aquaculture and is a recipient of EU subsidies (Guillen et al., 2019), with yearly mussel production increasing by up to 700 t in 2018, yet remaining the smallest producer within the EU. Similarly, as in the other EU countries, the yield in mussel culture failed to achieve the goals predicted by national plans for 2020 (NSNA 2021–2030).

In the last recent years, some serious obstacles have been preventing higher mussel production in the EU. They can be divided into biological as lack of seed, predation by fishes (in particular, gilthead seabream in the Gulf of Trieste), the spread of diseases, harmful algal blooms (HABs), deterioration of marine environment with variety of pollutants; nowadays microplastic is recognised as dangerous pollutant affecting mussels and their larval stages (Bringer et al., 2022), climate changes and their consequences as heat waves, extreme weather conditions which can harm infrastructure and slow growth or even increase mortality. Besides this, structural causes include conflict in spatial use, fewer areas available for mussel culture, low mussel prices, high depreciation costs, and

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low earnings (Avdelas et al., 2021). These are intrinsic causes, because the mussel production is technologically simple and open to the marine environment, leaving no control over the production. Only a few culture techniques are in use, such as raft, longline, bottom and 'bouchot' culture, depending on the marine environment (mostly on depth) suitable for mytillid species. Mussel farming faces almost no innovation and development in the production process.

Mussel farming in Slovenia started in the early 1970s in the Bay of Piran near a fishing reserve dedicated to enabling the spawning of the golden grey mullet (*Chelon auratus*). The first mussel farm plants started the production of *Mytilus galloprovincialis*, while current production includes more economically valuable species, such as the Venus clam (*Venus verrucosa*) and oysters (*Ostrea edulis*), which require more demanding techniques. This area allowed mussel farming without conflicts with trawling and net fishing. The first mussel cultivation was carried out by the company Droga Portorož (then TOZD Riba), and later mussel cultivation was carried out by fewer than ten individuals having the right to use cultivation plots and by the company Mariva Portorož. Production of Mediterranean mussels peaked in the 80 s and later consolidated into three small family companies. Mussel cultivation was extended to Strunjan Bay and St Jernej Bay near Debeli Rtič, where it is still cultivated today (Bolje et al., 2019).

A more consensual marine spatial planning and use of natural resources are needed due to increasing and intensive activities along the Slovene coastline, which caused an increasing number of conflicts in the use of marine resources. The strategic document for the period from 2021 to 2030 stimulates the development of both inland and marine aquaculture with coordinated spatial planning, optimisation of administrative procedures, compatibility of aquaculture with other activities, traceability of aquaculture products, innovation, research and data collection from aquaculture, animal welfare, preservation of biodiversity and resilience towards climate change, along with allocation of structural funds (NSNA 2021–2030; Čok et al., 2021). The next step comprised the examination of all predicted uses of the marine environment in Slovene territorial waters, which enabled the allocation of new areas dedicated to mussel and finfish farms away from the coastline (Flander-Putrle et al., 2020).

There is no detailed study so far dealing with mussel farming, techniques, the impact of environmental parameters on mussel growth or socio-economic aspects in Slovenia. The data about mussel farming are scattered and are mostly anecdotal descriptions of activities and simple introductions to farming techniques. The sector was neglected partially due to its extremely small size and low income, its small number of employees and its simple production techniques. Considering of recent climate change and uncertainty in the food supply, the interest in aquaculture has increased due to simplicity of production, the high nutritional value of mussels, and sustainability. Mussels are also carbon sinks and have a beneficial impact on the marine environment, and a short supply chain with low carbon imprint. The aim of the survey was to analyse in detail the progress and troubles in the artisanal mussel production based on interviews with Slovenian mussel farmers and to oversee possible opportunities and innovations to sustain the sector.

2. Material and methods

The present study is based on the collection of primary data using semi-structured interviews and secondary data from various sources [data on production and employment from statistical reports Statistical Office Republic Slovenia (SORS)] to describe the current situation of mussel farming in Slovenia. At the time of this study, four producers of mussels in Slovenia were registered, and three were willing to participate in the study. The interviews were conducted in December 2022 and January 2023. Interviews were performed using a semi-structured questionnaire, which was prepared by the authors of this study and confirmed in advance with the respondents. The questionnaire comprised 73 questions in total, divided into eight sections: general information about the producer, production technology, production and marketing, infrastructure and use of the environment, monitoring, problems, and solutions. Table 1 presents a summary of the questionnaire, and Table S1 the summarised answers. Respondents who objected to certain questions could skip the question without explanation. The answers were recorded, and the responses were evaluated from transcripts. Before analysing responses, we assigned a code to each respondent (P1, P2, P3) to ensure non-disclosure of their identity. One interviewer was responsible for all interviews and each interview was completed in one and a half hours. The main objective was to obtain information directly from the mussel farmers to identify the main challenges of mussel farming in Slovenia. Primary data was presented and summarised in the results section, and secondary data were included in the discussion and contrasted with the primary data.

3. Results

All active mussel farmers were invited to participate in the study; they received the questionnaire in advance via email and were asked to add comments if needed. Participation was voluntary; during the interview, the interviewee could refuse to answer if they felt uncomfortable with the question. The questionnaire was presented in Table 1 under the Material and methods section. Responses from the semi-structured questionnaire were summarised and presented in thematic units according to the questionnaire (see Table S1). Responses are presented below.

3.1. Summarised interviews of mussel producers in Slovenia

In Slovenia, four mussel farmers actively work on mussel production. Three of them were interested in giving answers to the questionnaire. All three mussel farmers have been in business for over a decade (the first from 1994, the second from 2003 and the third from 2000). They have different business models: the first interviewee has 50% mussel farming and 50% fishing, the second has mussel farming as an addition to the sea bass farming (which is their main activity), the third is primarily a mussel farming (90% Mediterranean mussels, 10% Venus clams). One has permission to grow oysters (not growing them currently), and the second is in the process of testing methods for optimal oyster growing techniques. The larger producer has a total of 20,000 hanging nets with Mediterranean mussels on two mussel farms, which enables him to grow three generations simultaneously. They have reported good collaboration with various public institutions, private companies, fishers, and their customers. Mussel farmers do not work in cooperation.

3.1.1. Description of the process of mussel farming, selling, and financial aspects

The mussel farms in Slovenia are designed as longlines for growing Mediterranean mussels (*Mytillus galloprovincialis*), having been transferred from mussel farming practices in Italy. The infrastructure for growing mussels consists of synthetic ropes, mussel farming nets, buoys, anchors, chains, concrete blocks, and underwater buoys. All producers have their own berths for vessels in the fishing harbour, stainless steel tables, forklifts, vans, and small trucks for transporting mussels. One mussel farmer has his own depuration system in operation, the capacity of which is made available to others on request. Equipment is mainly bought in Italy. Ropes, buoys, and chains last up to 10 years, while nets are for single use only and are disposed of after use. Weather-related damage (storms, wind, waves) is rare, and the tearing and loss of ropes, farm nets, buoys or mussels occur extremely rarely or never.

Work automatization is possible during harvesting and packaging and is affordable only for larger producers (i.e., mechanical harvesting and cleaning of mussels on board; during the most intensive season, volumetric weight is used on board and products are packed on board, own depuration system). The other two mussel farmers perform most of their work by hand, because machines are too expensive, or the main

Table 1
Summary of questionnaire sections.

Section	Number of questions	Topic	Description of the section
1	1–5	General information on the producer	The questions aim to introduce the mussel farmers and explain how they started production, what obstacles they had to overcome from the beginning, what their business model is and how they cooperate with public institutions such as marine protected areas, municipalities, ministries of environment and agriculture, relations with main customers and fishers. We were also interested in whether they wanted to participate in different projects (national, international) and in which topics they were interested.
2	6–21	The process of mussel farming	The section provides an overview of mussel production (species, rearing system, size of mussel farm), origin of seeds/spat, monitoring of growth, transplantation of mussels, maturation of gonads and spawning, harvesting time, presence of non-native species and possible negative impacts. We were also interested in the production process and the labour automation.
3	22–29	Production and sale of mussels	The questions relate to discharges, the place and manner of mussel sales, advertising strategies, consumer habits (demand for mussels), monitoring physical-chemical parameters, and monitoring by the authorities (mandatory monitoring).
4	30–38	Production facilities and use of space	The questions relate to the infrastructure for cultivation at sea and on land, the longevity of the infrastructure and the disposal of litter. The second part is about subsidies for infrastructure.
5	39–42	Inspection and controls	This section lists the authorities responsible for the various inspections on mussel farms and the efforts made by mussel farmers to produce the required documentation.
6	43–51	Financial aspects	Description of the financial aspects, the most common costs in the production and maintenance of infrastructure, labour costs, allowable subsidies and '*de minimis*' financial aid, and finally, the cost of medical treatment in the mussel farms.
7	52–60	Difficulties and obstacles	The section provides insight into the difficulties and obstacles in mussel production and the negative effects of events in the ecosystem on mussel growth, including parasites and diseases. Special attention was given to raising awareness of microplastic pollution in the sea.
8	61–73	Solutions	Description of possible solutions for mussel production from the owner's perspective.

focus is fish farming.

Mussel growth is evaluated by the measurements (also automatically by size sorting machine) or visual estimation of shell length. All three mussel farmers only monitor mussel spawning – visible as a milky liquid in the seawater. Mussels are harvested all year round, except during exceptional events such as HABs (prohibition of selling due to possible poisoning of consumers with accumulated toxins from dinoflagellate algae causing HAB) or microbiological contamination. While there is maintenance work and harvests on the mussel farms throughout the year, harvest is more intensive during the summer due to the increased demand for mussels in restaurants.

The transplanting of mussels is required two or three times per year (sometimes four times). Mussels are usually sold when they reach 4–7 cm in length (growth period of 2–2.5 years), but the market size differs slightly between producers. Most mussels (60–70% throughout the year) are sold directly to restaurants, fishmongers, or wholesalers in Slovenia. The gross weight of sold mussels ranges from 3 to 7 t per year (smaller producer) to 150–200 t per year (larger farmers). The price on the market is 2.5–4.5 € per kilogram. Mussel farmers do not advertise their products actively; they already sell everything. Mussel farmers notice that the demand for mussels is increasing.

In the past, mussel farmers bought juveniles in Italy, and nowadays, they allocate money to set up infrastructure at sea and on vessels and cut costs when buying juveniles. Traditionally, they collect juveniles on ropes in the vicinity of mussel farms. During the production process, a small amount of non-marketable products appears, and small mussels are re-seeded back to the nets and grown until they reach market size. A portion of mussels in the nets grows more slowly due to less favourable conditions in the bunch of mussels. Small losses may occur occasionally (e.g. mussels die during prolonged storage for seeding when weather conditions do not allow work at sea). Mussel farmers differ in checking the fouling organisms on the mussels' shells and the cultivation infrastructure. Two active mussel farmers check for it, and one regularly cleans the infrastructure in the mussel farm. The non-indigenous species noticed by the mussel farmers are the bluefish (*Pomatomus saltatrix*), the Pacific oyster (*Magallana gigas*), ctenophores, and tunicates.

In general, they stated that labour and fuel are the majority of costs. They spend most of their resources on vessel maintenance (around 5000 € per year) and the maintenance of infrastructure at sea (mussel farming equipment - synthetic ropes (270–300 €), a buoy (70 €), nets for mussels (60–65 €), nets and clips for mussels (60 €), on land and in the fishing port. All the mussel farmers interviewed stated they do not receive subsidies or grants to purchase equipment (fixed assets). In the past, they have received 60% of grants under EU-funded projects, but not for consumables (e.g. mussel farming nets). There are two reasons why mussel farmers in Slovenia do not benefit from EU funds: applications are too complicated, and they must pay in advance and wait six months for reimbursement.

3.1.2. Inspection and controls

Several administrative bodies are responsible for monitoring mussel farms: Administration of the Republic of Slovenia for Food Safety, Veterinary and Phytosanitary Affairs, Health Inspectorate, Market Inspectorate, Fisheries Inspectorate, and Financial Inspectorate. All mussel farmers use registration documents for traceability (calibration of weight, mussel species, type of sale, shipment and delivery note). They must keep monthly and annual financial records; data are also reported once a year to the Slovenian Water Authority (in hectares used area) and to the Ministry of Agriculture, Forestry and Food (Directorate for Food and Fishery). Mussel farmers complain that bureaucratic matters take too much time and are very demanding. Mussels produced for trade must undergo to regular monitoring: samples of mussels are delivered on almost a weekly basis for monitoring under the Administration of the Republic of Slovenia for Food Safety, Veterinary and Phytosanitary Affairs. Between 1 and 1.5 kg of mussel samples are taken to analyse toxins, and 0.5–1 kg to analyse bacterial contamination. The analysis of

hazardous metals in mussels is carried out once or twice per year. There is no regular monitoring of physical and chemical parameters dedicated to improving mussel production. Monitoring of algae and its toxins could be improved as faster receipt of the results of this monitoring could be used to quickly stop the harvesting of mussels as soon as possible and thus prevent unnecessary costs.

3.1.3. Difficulties and obstacles

The main obstacle to Slovenian mussel farming is obtaining a concession to grow mussels (it can take years) and the cost of labour and vessels (a berth in the fishing port). Initially, there was a problem in classifying farming areas into zone B, which required a depuration process of mussels before selling despite HABs' presence. In general, costs are increasing, and mussel production is decreasing yearly. The main reasons for the decrease in mussel production are ctenophores predation on larvae, high sea temperatures in the summer, and direct predation of gilthead seabream on mussels, the latest causing significant economic losses, which can be up to 80% of production. Damage increases exponentially over the years, and one of the mussel farmers decided to stop farming mussels so intensively. In the late summer of 2023, gilthead seabream predated one third of mussels in one night (Primorske novice, 15.9.2023). The loss estimation before 2023 in the Bay of Piran and the Bay of Strunjan was 50% of their production due to predators; in 2023, the third area, Debeli rtič, was also predated by gilthead seabream. All respondents stated that they do not use fish deterrents.

Less critical is economic loss due to blooms of HABs. When this phenomenon occurs, sales are stopped for three weeks, and the mussels then remain in the purification system for cleaning without any significant economic loss. Toxin poisoning due to HABs occurs about once a year. The economic loss depends on the onset of HABs. If it occurs in September, the economic loss is greater due to a higher harvest; the loss is smaller in late autumn (November and later months) because of the smaller harvesting season. In the recent years, mussel's slower growth during hot summer months and a lower number of seeds were noted, even though more ropes have been installed to attach larvae. Unlike in Italy, where warm water in shallow seas causes an irreversible detachment of mussels, in Slovenia, until now, a significant decrease in production due to high seawater temperatures and lower rainfall has not been observed, according to their opinion.

3.1.4. Solutions

Mussel farmers are convinced that mussel farming is highly dependent on natural processes in the sea. All agree that it is crucial to expand mussel farming away from the coast (to open sea) with a view towards a future change in cultivation techniques (e.g. closed aquaculture). At the time of this survey, all available water rights had been allocated, limiting any possibilities for expanding mussel farming. While one of the mussel farmers believes that the size of his farm is sufficient, he foresees possible issues with finding new customers at the existing selling price. The second mussel farmer focusing mainly on fish farming believes that the size of his farm is insufficient for his mussel farming business to survive on its own. The third mussel farmer pointed out that expansion of mussel farming is only possible away from the coast (one nautical mile or 1852 m) as proposed in the new maritime spatial plan).

While one mussel farmer has no intention of farming other mussel species (the smallest producer, in addition to fishing), the other two would like to grow other species (the main obstacle is the high price of spat). One of those two has already invested a lot of time and money in developing oyster farming techniques and is confident they will optimise the techniques and succeed. The price for oysters is good, and recent attempts to farm oysters have been promising.

Two mussel farmers identified the need to receive investment grants and funds to compensate for income losses due to extreme events as well as funds to promote organic farming and mussels as healthy food. One mussel farmer proposed optimising '*de minimis*' funds in the same way as in Croatia. In Slovenia, this support covers half the cost of one worker per year, with worker's salaries being the biggest expenditure. Mussel farmers think bureaucratic procedures and ease of access to EU structural funds must be simplified. Good and widely recognised brands could increase the sale of mussels (e.g. mussels from Istria). There is also a need to gain knowledge to improve growing practices (especially for oysters and Venus clams) and increase their production.

4. Discussion

Slovene mussel production is a small economic sector that brings in less than 1000 t per year of mostly Mediterranean mussels, and, in a smaller proportion, Venus clams and oysters. The total area dedicated to mussel harvesting is 510.640,22 m^2 (51 ha). Currently, seven entities have registered marine aquaculture activities in the National Central Aquaculture Register (CAR database), but only four are active in the sector (three of these four have voluntarily participated in the survey). Only the two largest producers are equipped with onboard mechanical shell cleaning technology and automated packaging systems (Figure S1). The smaller of these producers cannot afford work automatization, and its business model is 50% mussel farm and 50% fishing. The other producer has a mussel farm in addition to a sea bass farm and does not sell mussels on the market.

Diversification in the sector is not extensive and includes only touristic trips with gastronomy and educational activities or custom-tailored underwater services. There is no mussel processing, and mussels are sold as raw products (with byssus threads) directly from farmers to fishmongers or larger retail stores. All interviewees mentioned the availability of permits as an obstacle, since obtaining one is laborious and takes too long (three years to obtain all permits, a similar situation to that in Ireland (EUMOFA, 2022); one producer even financed a study on the environmental impact assessment needed to obtain permits. Regular administration and reporting to authorities take a significant amount of time (estimated at five hours per week). The main expenses are for labour, followed by the infrastructure maintenance (vessels, vans, electricity for cold storage). Two of the mussel farmers have their own depuration facilities and allow others to use them.

The consumption and demand for mussels are increasing in Slovenia; consequently, advertising is unnecessary. Mediterranean mussels mostly sell in Slovenia and Croatia, while the more valuable Venus clams and oysters sell in the more demanding markets of Italy and France. The whole supply chain is run by mussel owners (from farms to stores and restaurants).

The production of Mediterranean mussels has been steadily increasing, the main obstacle being the limited area for cultivation to increase production, occasional HABs and nowadays predation by gilthead seabream and flatworms. Spat is collected near mussel farms on ropes and then seeded. In the past, mussel farmers occasionally bought spat but found it unsustainable for their business due to the high price. In general, they do not worry about environmental concerns such as pollution and microplastics, although one expressed concern about building a new gas terminal in the vicinity of mussel farms at Debeli rtič due to impacts on mussel production.

Mussel farmers noticed a lack of knowledge, a limited knowledge base, few dedicated learning opportunities in their business, and lack of innovations in production. They expressed a need for faster exchange of information between authorities, especially during a ban on selling due to HABs. Mussels produced in Slovenia do not have any certification schemes (e.g., organic farming, Aquaculture Stewardship Certificate, Protected Denominations of Origin); farmers build on their own brand and recognition by advertising and presenting on their websites.

The mussel cultivation floating line technology (longlines) was adopted from neighbouring Italy and is still used today. Each floating line consists of floats connected by ropes, with the floating line anchored to the seabed at each end. The line may consist of one or two parallel ropes. Between the floats (barrels), nets with mussels are suspended

from the ropes. The seed or spat (larvae in the phase of pediveliger) is collected on ropes near the mussel farms and then seeded into cotton nets first and later into polyethylene nets. There is no hatchery for mussels in Slovenia or in the vicinity. During the growing cycle, the mussels should be transplanted several times into nets with a larger mesh. They reach a market size of about 5 cm at least in 14–18 months. In the last few years, Venus clams and oysters are also farmed in small quantities in special baskets on the seabed. In the past, transplantation of mussels, re-seeding and cleaning epiphytic organisms from mussel shells were made by hand with sieves on board, with a simple winch used to lift nets. Investments were mostly limited to infrastructure; two applications were submitted by 2020 dedicated to building new breeding lines for 254.824 € of EU structural funds (NSNA 2021).

Fishing and aquaculture sectors in Slovenia employ about 250 persons and remain important for a few small producers, mostly family owners. Fig. 1 presents the number of employees and form of employment in the marine aquaculture sector from 2008 to the present (SORS; 2023). The coefficient of determination (R^2) value indicates how well the linear regression line explains the variation of the number of employees (dependent variable) over the years (independent variable), with a value closer to 1 indicating a better prediction of the linear model. In general, the sector has mostly part-time employment due to seasonal work with family members helping at work. Most of them are self-employed part-time only. In 2020 and 2021, the number of employees dropped, and the ratio between full-time and part-time employees became equal (2019 and 2020) but increased slightly in 2021 in favour of full-time employees. This coincided with the COVID-19 crisis, which interrupted perishable food supply chains and interfered at many stages of the production process from hatchery to market. Cancellation of employment is the consequence of the COVID-19 crisis (especially due to restrictions on social contacts and cancellations in restaurants, catering, and hotels).

A global survey was conducted to evaluate the COVID-19 pandemic impacts on all levels of the perishable supply chain in the aquaculture sector and exposed a variety of issues, including mitigation measures (e.g. direct sales to customers, online retail system, more food processing like freezing and smoking) and financial aid strategies. Survey responses identified the potential causes of disruption, ripple effects, sources of food insecurity, and socio-economic conflicts in the supply chain (Mangano et al., 2022). A similar survey was conducted in the EU countries (Nielsen et al., 2023) and in neighbouring country Croatia and it indicated higher economic loss than job loss, and bivalve producers experienced a higher drop in sales (Pećarević et al., 2023).

Nowadays, mussel farms are in the Bay of Piran, Bay of Strunjan and St. Jernej Bay near Debeli Rtič. The total mussel farm area in 2019 was 900,340.73 m^2 (90 ha), with an annual return of 25 t ha^{-1}. In the future, the area for mussel farming can be increased by an additional 76 ha (Flander-Putrle et al., 2020). Table S2 provides more details on the area for mussel farms. The mass of production in aquaculture constantly grew from 77 t in 1990 (see Fig. 2) to 798,3 t in 2019, mostly due to the increase in the production of Mediterranean mussels. The sharp drop in mussel production during 2010–2012 was due to the persistent occurrence of HABs (see Fig. 2), which completely stopped the harvesting and selling of mussels (cf. Francé et al., 2018; Zingone et al., 2021) and caused additional costs due to depuration processes and increased use of energy.

The mussel production grew until 2019, while in 2020 and 2021 the production was half that in 2019 (Fig. 2). The National Strategic Plan for the Development of Aquaculture in the Republic of Slovenia 2014–2020 (NSNA 2014–2020) set a target to increase mussel production from 311 t to 1000 t in 2020. This target was not achieved and was set in the new plan until 2030. Production in marine aquaculture in Slovenia (mussel and finfish aquaculture together) overcame landing from fisheries in 2012 based on subtracted data from FAO for Slovenian capture fishery and aquaculture (FAO, 2023), due to the continuous depletion of fishery landings in the last three decades (see Figure S2 for comparison). In 2017, mariculture exceeded the mass of catch fisheries by a factor of five, mainly due to the increased production of Mediterranean mussels (Bolje et al., 2019).

In 2020 and 2021, the mussel production dropped to 400 t. Before 2020, the loss of income was mainly due to HABs (compare Fig. 2 and Fig. 3). Comparison with data on the closure of mussel farms can help explain the severe drop in production due to algal toxin presence in mussels, from around 300 t to less than 100 t, and then the increase in production in 2011–450 t. After 2013, production increased steadily to 2019 (Fig. 3). Between 2019 and 2021, the areas used for the infrastructure for bivalve production also increased (green line in Fig. 3).

According to annual mussel production data (SORS, 2023) and the used (active) area of the mussel cultivation plots in 2018, annual production in 2018 was 15.2 t per ha^{-1}. However, depending on the stocking density of individual mussel nets, this calculation could be significantly higher (estimates of up to 60 t ha^{-1} over a growing cycle of 18 months). The very conservative annual production estimate is 12 t ha^{-1} (Flander-Putrle et al., 2020). New areas, more than one nautical mile (1852 m) from the coast, are predicted and in this case, the nets with mussels could be longer due to the greater depth of the sea (more

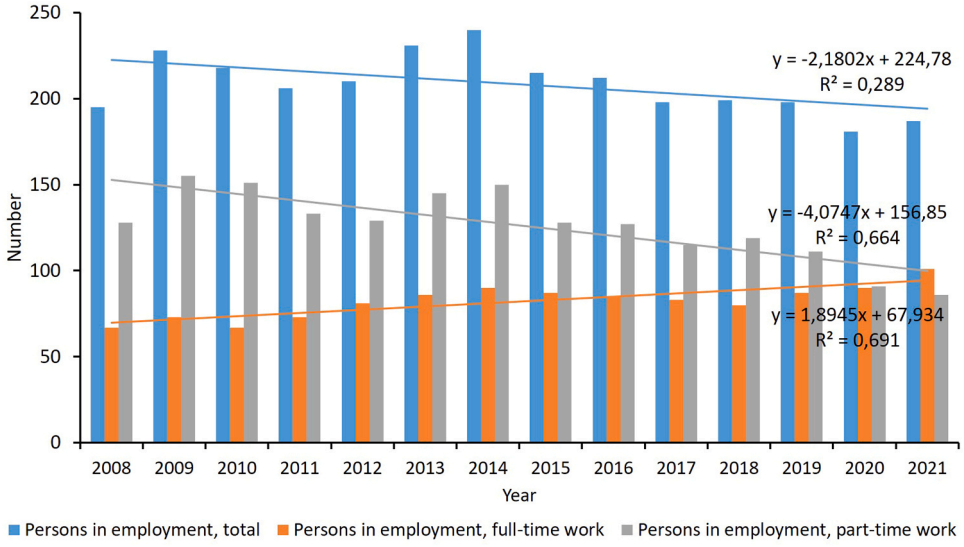

Fig. 1. Individuals employed in marine aquaculture in Slovenia broken down by year and type of employment (SORS; 2023).

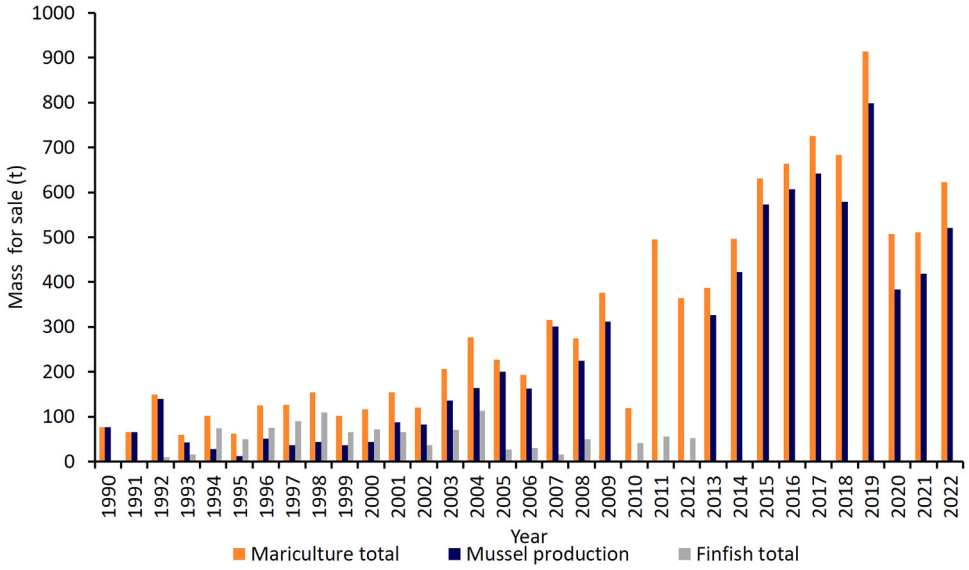

Fig. 2. Aquaculture (inland and mariculture) production in Slovenia, breakdown for mussel production. Missing finfish total data from 2013 is due to lack of confidentiality (only one producer).

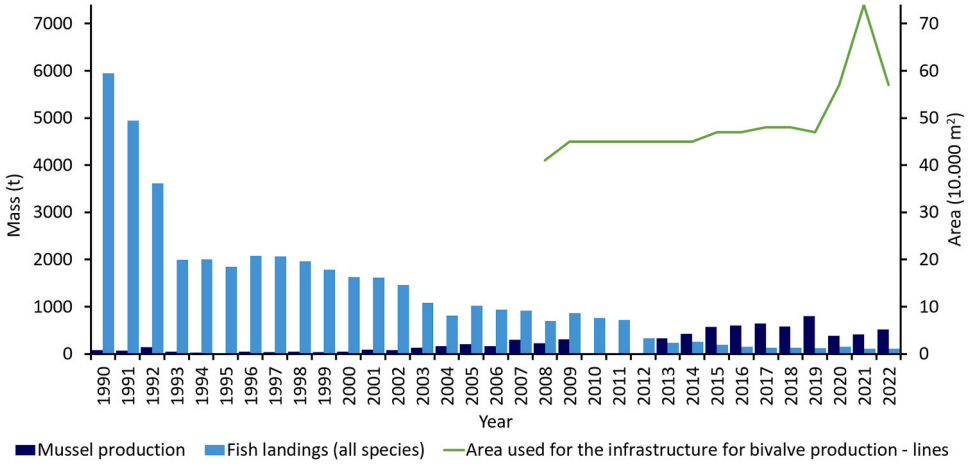

Fig. 3. Annual mussel production in Slovenia, fish landings (all species) and area used for bivalve production.

than 15 m), and a larger quantity of mussels could be produced per unit area (Flander Putrle et al., 2020). New areas would enable better mussel production because of seawater temperatures more suitable for mussel growth, especially during the hot summers, reducing the risks of exposure to biotoxins such as phytoplankton blooms and exposure to diseases, parasites or terrestrial sources of contamination (pesticides and other pollutants). The setup of multitrophic aquaculture is desirable, and conditions in the proposed area allow fish and mussel farms as well as the growth of clams at the sea bottom (in the Bay of Piran and Bay of Strunjan). The multitrophic approach has many beneficial effects on the environment and can remediate the effects of traditional aquaculture practices (a situation in the Adriatic Sea was reviewed by Tičina et al., 2020).

Global mussel production increased by 7% between 2011 and 2020 at the expense of higher production in China and Chile (EUMOFA, 2022). Recently, a pan-European study, based on stakeholders' information, indicated aquaculture mussel production in the EU peaked in the late 1990s at more than 600,000 t; since then, production volume dropped by 20% to 480,000t in 2016 (Avdelas et al., 2021). As mussel production represents more than one-third of EU aquaculture production, this decrease is an important contributor to the stagnation of EU aquaculture due to several reasons which contribute to the decline of production as the spread of diseases, HABs, lack of spat, predation and low earnings (Avdelas et al., 2021). Such causes may have been exacerbated by local conditions such as the small size of mussel enterprises (Villasante et al., 2013; Theodorou and Tzovenis, 2017), lack of innovation in mussel production processes (Labarta and Fernández-Reiriz, 2019), carrying capacity of ecosystems to support mussel production (Taylor et al., 2019; Romero et al., 2023) and the impacts of climate change (Lassoued et al., 2021).

One of the critical problems is HABs (Zingone et al., 2021; Francé et al., 2018), the occurrence of which is unpredictable. The most worrying biological pressure is predation by gilthead seabream (Šegvič-Bubić et al., 2011; Glamuzina et al., 2014; Richard et al., 2020) and caused Slovenia to incur a 30 per cent of loss in younger mussels by predation during late summer 2023 (Primorske novice). While preparing the manuscript, gilthead seabream devastated the youngest cohorts of mussels, leaving empty nets (Figure S3a and S3b) and no harvest for the next two years. During the summer of 2023, we also noted predation by flatworms (A. Ramšak, personal observation), but the data to estimate economic loss due to their predation in Slovenia are not available yet. According to owners' opinion, predation pressure would be smaller

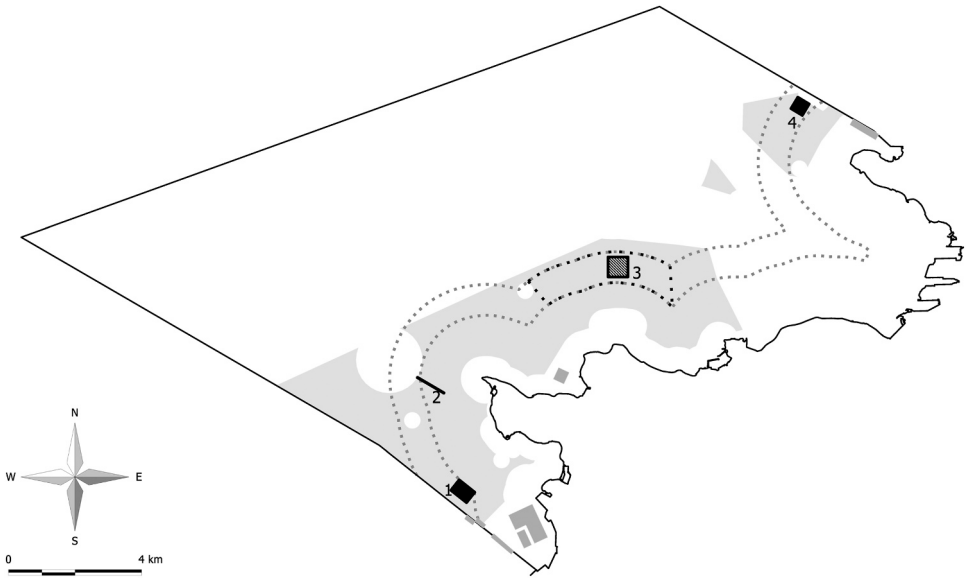

Fig. 4. New and existing areas for mussel and finfish cultures along Slovene coastline (adapted from Flander-Putrle et al., 2020). The dashed line depicts 1 and 1.5 nautical miles (1852 m and 2778 m) from the coast, the grey surface depicts available areas for mariculture, and the black squares depict new sites for mussel culture plots.

at farms away from the coastline and less likelihood of microbiological contamination, which can cause the closure of trading. Farming away from the coastline has not yet been addressed under Slovene conditions or evaluated from many relevant aspects. Occasionally, as mitigation action, fishery authorities allow fishers to catch gilthead seabream near mussel farms to reduce predation on mussels.

Mussel farming is an open system that inseparably depends on available phytoplankton as food, seawater temperature, and currents, among others. In the past, the Gulf of Trieste was a very productive environment, supporting mussel production, while in the last decade, it became more oligotrophic (Mozetič et al., 2009) and warmer (Kralj et al., 2019). Those aspects are not understood, and their consequences on mussel production in the Northern Adriatic have not evaluated. Mussel production is perceived by society as a sustainable production of seafood with a low carbon footprint and minimal impact on ecosystem services.

A report from the Scottish Aquaculture Research Forum (Fry Meyhoff, 2012) found that rope-grown mussels have a carbon footprint of just 0.25 kg CO_2 equivalents per kilo of mussels harvested, or 0.6 kg CO_2 equivalents per kilogram of mussel meat. An important regulatory ecosystem services of mussel farms is carbon sink (fixation of CO_2 and $CaCO_3$) and removing nutrients (Alleway et al., 2019). The carbon footprint is calculated to be 649 kg CO_2-equivalent per t of mussels harvested and 1685 kg CO_2-equivalent per t of oysters harvested (cf. Suplicy, 2018 and references therein). According to this estimation, mussel farms along the Slovene coast fixed roughly 518 t of CO_2 during 2019 at 798 t production.

Mussels filter water for phytoplankton and, as their tissues are approximately 1.4% nitrogen and 0.14% phosphate by weight (Shumway et al., 2003; Rose et al., 2015), these nutrients become stored in the mussels, and are removed from the marine environment when the mussels are harvested (Petersen et al., 2016; Martini et al., 2022). Each mussel can filter between five and ten litres of seawater and from 15 mg to 150 mg of particulate organic and inorganic material per hour, thus reducing turbidity and both directly and indirectly removing nutrients from the water (Prieto et al., 2020). Estimating trade-offs between mussels' remediation and organic deposition below grow-out structures (e.g. cages and tables) is critical, as this affects benthic biodiversity and substrate chemistry (Custódio et al., 2019).

The detrimental impact of mussel farms impacts the creation of secondary hard benthic habitats with dropped shells. These issues are not appropriately addressed in Slovene aquaculture. We should not neglect the detrimental effects of mussel farms on the environment, such as phytoplankton depletion, modifying the benthic environment and species assemblages, altering local hydrodynamics, increasing marine litter and facilitating the spread of unwanted species (Forget et al., 2020; Suplicy, 2018; Timmermann et al., 2019). Infrastructure such as longlines can change water flow; if flow increases, it can lead to erosion of surrounding areas, while sediment deposition can occur if flow decreases (Cabre et al., 2021). Many of these detrimental effects are still not investigated in detail in mussel farms in the Slovene territorial sea. More detailed studies in the field with measurements of currents and the carrying capacity of the environment are required.

Although some solutions and innovations are available in the sector, they are rare and more suitable for implementation in larger production (e.g. mussel farming in Galicia; Labarta and Fernández-Reiriz, 2019). Possible innovation is orientation towards the use of mussels as nutritional and beneficent food for human health and exploration of the by-products from mussel production (Suplicy, 2018). These solutions are not implemented in Slovenia due to small mussel production, sold as raw products, and the resulting insignificant amounts of by-products.

There are no existing quality schemes for aquaculture products in Slovenia. The supply chain is short; producers have their own marketing and sale channels (packaging facilities, transport vehicles), and the majority of mussels are sold in Slovene retail shops and fishmongers. In Slovenia, this short perishable food supply chain is perceived as an advantage for consumers (Janeš et al., 2017; Mavrič et al., 2021). Two producers make more efforts in marketing by organising touristic trips, cooking experiences and educational workshops, which raise recognition level and can serve as a positive example of how to make mussels more valuable and recognised.

Responses from the interview pointed out that they are not interested in additional labelling or branding of mussels, because existing mussel production fails to meet the demands of the market. Their opinion is that the label would raise the price of mussels. In the previous study within the aquaculture sector, common brand and traceability were exposed as needed issues (Mavrič et al., 2021). There are examples of Protected Designation of Origin, like Scardovari mussels, Galician mussels, and Moules de Bouchot de la Baie du Mont Saint-Michel (EUMOFA, 2022). A positive example is the farming of Venus clams, which are highly valued

bivalve mollusc (a price of around 15–22 € per kilogram) and is in wider use in gastronomy after protection and prohibition of sales of European date mussel (*Lithophaga litophaga*).

Scientific investigation of mussel farming and related issues is very scarce, and this gap should be overcome for the benefit of developing mariculture in Slovenia. Similarly, there is no study program in aquaculture; selected topics from aquaculture are scattered at Slovene universities under several bachelor programs. In the last two decades only, a few studies focused on mussel farming. The Slovenian study *Factors Which Influence Bacterial and Viral Infections in Mussels* (2014–2016) focused on the presence of human pathogens in Mediterranean mussels (Henigman et al., 2015). The FishAgroTech Interreg project between Slovenia and Italy during 2016 and 2019 was dedicated to fishery and marine aquaculture, and owners of mussel farms actively participated in workshops and questionnaires to express their needs and possibilities for innovations and development. One of the results was the initiative to set up a platform with data relevant to aquaculture (HAB blooms, currents, seawater temperature) with an ambitious plan to design a prediction model.

Mediterranean mussels were used in biomonitoring from 1999 to 2010 (UNEP MAP Programme and Barcelona Convention) under the umbrella of the Environmental Agency of Slovenia. Mussels were used as sentinel species or were transplanted from mussel farm to the site of exposure and mussel farms were included as reference sites (Ramšak et al., 2012; Tsangaris et al., 2016; Perić et al., 2017; Bajt et al., 2019). Mussel farms were included in a national environmental monitoring program, physicochemical parameters were measured, and the phytoplankton community was analysed for the presence of potentially toxic Dinophyceae species. Several publications were published dedicated to recording HABs and the harmful effects of HABs on humans via the consumption of mussels (Francé et al., 2018). A project (*Dobro za morje -Dobro zame* 'Good for the sea - Good for me') dedicated to increasing awareness of the public for environmental problems and sustainable mariculture was carried out with many workshops (as well as a cooking experience) and public events during 2022, financed by EU structural Funds and LAS Istre.

5. Conclusions

Mussel farming in Slovenia is characterised as a small sector and the entire perishable supply chain is covered by mussel farm owners. The production of Mediterranean mussels (*Mytilus galloprovincialis*) has increased steadily, with the main obstacles being a limited area for cultivation, occasional harmful algal blooms, predation by gilthead seabream and flatworms. In the last decade, the cultivation of Venus clams and oysters was introduced, which is more demanding, but yields a higher profit.

Mussel farmers are self-taught and miss more options for formal education or a knowledge centre for stimulating the transfer of knowledge and innovations. Diversification in the mussel farming sector remains low. Despite being a small sector, certain strengths make it more resistant to market fluctuations (e.g. high and increasing market demand, no need for advertising, short supply chain, and mussels being recognised as a Mediterranean tradition and incorporated into a healthy Mediterranean lifestyle and gastronomy). Mussel farmers are willing to expand production areas away from the coast to more suitable areas with deeper seawater. Potentially conflicting activities and interests arise from commercial and recreative fishing, tourism, maritime transport (Port of Koper), nature and cultural conservation.

In conclusion, mussel farming in Slovenia faces several open issues: 1) how much can the mussel production be increased (the carrying capacity of the Slovene coastal sea), 2) what new areas are available for expanding mussel farms, 3) whether further diversification of the sector is possible or necessary (tourist tours, gastronomy and custom-tailored services), 4) the production of higher profit species (e.g. oysters), 5) developing higher quality and more sustainable products, and 6) the challenges and opportunities for brand development and product traceability.

CRediT authorship contribution statement

Manca Kovač Viršek: Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Uroš Robič:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Tine Bizjak:** Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis, Data curation. **Andreja Ramšak:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.aqrep.2024.102166.

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