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Charting the future of marine biotechnology: educational strategies for empowering Europe's blue bioeconomy workforce

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This study provides useful insight into the current state and recent developments in blue (marine) biotechnology education (BBE) in Europe. A questionnaire assessing awareness and interest in blue biotechnology (BB) was conducted among students in their final year of upper secondary school in a selection of European countries. Results demonstrate that there are great regional differences in students' recognition of BB; recognition of BB is relatively poor (though biotechnology knowledge is relatively good). This illustrates the lack of early education and ocean literacy. The interest in BB studies varied by country. Non-formal science, technology, engineering, and mathematics (STEM) activities, especially visits to research institutes and private businesses, help raise awareness. The review of education programs conducted in this study revealed that only a small number of programs are dedicated to BB and that it is not well integrated into existing curricula. Early ocean literacy, lifelong learning opportunities, and the inclusion of entrepreneurship and interdisciplinary skills in education are essential for developing a workforce capable of driving the future of the blue bioeconomy within the broader objectives of the EU Blue Economy Strategy and European Union (EU) Bioeconomy Strategy. To advance BBE, we propose the following recommendations: 1) incorporate and increase ocean literacy and BBE at the primary and secondary school levels; 2) support lifelong learning and adaptation to emerging technologies; 3) build collaborative ocean education networks; 4) bridge education communities, research and industry; 5) encourage entrepreneurship; 6) harmonise postgraduate BB programs; 7) establish joint European MSc and PhD degrees; and 8) align funding and BBE activities with national and regional gross domestic product (GDP) contributions for the BB sector.

KEYWORDS

blue bioeconomy, blue biotechnology education, entrepreneurship, interdisciplinary skills, lifelong learning, ocean literacy, STEM education

1 Introduction

Biotechnology is a well-established scientific field known for its applications, which use living organisms or their metabolites to produce beneficial products for society, the environment, and industry (Luiten et al., 2003). This broad knowledge area encompasses a wide range of products, from high-value pharmaceuticals to low-value biofuels (Pérez-López et al., 2018). To differentiate its various sectors, colour-based classification has been used in the past, for example, white biotechnology for industry, green for agriculture and blue for marine (blue) biotechnology (BB) (Kafarski, 2012).

The OECD (2016) defines BB as the application of science and technology to living aquatic organisms, leading to knowledge, goods, and services. The immense potential of BB is attributed to the vast diversity of marine organisms, metabolites, biopolymers, and enzymes with broad pharmaceutical and biotechnological applications and undiscovered biological mechanisms (Caruso et al., 2020; Jimenez et al., 2020). Indeed, BB is a rapidly expanding sector with significant potential for development (Vincx et al., 2018).

In Europe, this sector is governed at national (e.g., smart specialisation strategies) and international levels. The Blue Growth Strategy (COM, 2012) is aimed to promote sustainable economic growth in the marine and maritime sectors by supporting research in the BB sector, with the expectation that the EU would become a producer of mass-market marine aquatic products. In 2021, the Sustainable Blue Economy Strategy (COM, 2021) was approved, where BB is considered an economic activity related to oceans, seas, and coasts. In November 2025, the EU Bioeconomy Strategy was published (COM, 2025), reconfirming the potential of bioeconomy as a driver for competitiveness, while encouraging Member States to promote bioeconomy-related education, training, and re-/up-skilling programs.

In addition to the traditional sectors (fisheries and aquaculture, maritime transport, shipbuilding, coastal tourism, offshore oil, and gas extraction), the blue economy is witnessing the growth of innovative sectors such as ocean renewable energy, biotechnology, and desalination (COM, 2021). In terms of its size, the global blue economy would be comparable to the seventh-largest economy in the world (Global Environment Facility (GEF), 2018). Regarding direct Gross Value Added (GVA), the biotechnology industry's contribution of €34.5 bn accounts for about 1.51% of the European industrial sector (Haaf et al., 2021). This is approximately one-third of the computer, electronic, and optical products manufacturing sector. The highest direct GVA is generated by pharmaceutical biotechnology (€29.9 billion), followed by industrial biotechnology (€4.5 billion) and agricultural biotechnology (€134 million). The global BB market size reached USD 5.9 billion in 2022 and is projected to reach around USD 11.7 billion by 2032, increasing at a CAGR of 7.09% during the forecast period from 2023 to 2032 (Precedence Research, 2024). BB is a relatively new industry when compared to other well-established biotechnology fields. Despite its growth potential, many EU Member States and regions still view BB mainly as a research area rather than a key economic sector, and Europe accounts for only 13% of patents filed for the use of marine molecules in innovative applications (Doussineau, 2020). This limited access to developing new products slows growth and job opportunities in this field. As the European Commission's policy landscape evolves through the above-mentioned strategies, education and skills development are becoming increasingly important for advancing BB. Innovative knowledge-driven ecosystems with skilled employees are more important than ever for a sustainable, resilient, and competitive agri-food and bioeconomy system. This is an important prerequisite for achieving the vision of the European Bioeconomy by 2040, where it is stated that breakthroughs in biotechnology and biomanufacturing make biobased solutions competitive and scalable through skills and capability building, investment certainty and reliable biomass supply (COM, 2025). The EU aims to build a skilled workforce, and BB has significant potential in areas such as aquaculture, marine-based food and pharmaceuticals, and climate adaptation (Duarte et al., 2017; Raja et al., 2024). However, its growth relies on substantial human capital, expertise from various fields, and a clear understanding of stakeholders. This means that adequate opportunities for human capital development should be provided either before (i.e., during formal education) or after entering the workforce (Rotter et al., 2023).

In some European regions (e.g., the Mediterranean), access to specialised lifelong education and BB training was identified as one of the main bottlenecks for the sector's advance (Rotter et al., 2023). The lack of suitable formal education systems has also been recognised at the policy-making level. An example is the Blue Careers call in Europe, initiated in 2016 as part of the European Maritime and Fisheries Fund Work Program to boost the Blue Growth Strategy (European Commission (EC), 2016). Its objective was to create educational programs to improve the skills of individuals already employed or seeking careers in the blue economy. To compensate for the lack of specialised formal education in the blue economy, numerous projects have been implemented across Europe. One example is a Blue Generation project funded by the European Economic Area (EEA) and the Norway Grants, which focuses on educating people aged 15 to 29 and encouraging them to pursue sustainable careers in the blue economy across Greece, Spain, Portugal, Bulgaria, and Poland (BlueGeneration, 2025a). Within this initiative, the Blue Career Job Platform was launched to support job searches, training, and internships across different areas of the blue economy. Taking these efforts a step further, the EU project BlueBioTechPreneurs (2025) aims to promote collaboration between universities and businesses to support blue careers. One of the first outcomes is a platform called BlueBioMatch (2025), which connects students, researchers, and industry professionals who have experience in or want to develop careers in the blue economy, including BB. Despite these efforts, many sectors of the blue economy still struggle to attract people with the necessary skills. BB, being highly interdisciplinary and with diverse applications, challenges educational systems. Key competencies essential for the Industrial Revolution 4.0 (OECD, 2015), BioIntelligent manufacturing (Maiser et al., 2022), and the new EU Biotech Act (Biotech Act, 2024) - including information literacy, soft skills, creative thinking, and adaptability - are often lacking or insufficiently integrated into secondary and higher education curricula. The European Commission identifies several areas of concern in the blue economy sector, including the capability and expertise gaps between education options and labour market needs, lack of communication and collaboration between education and industry, lack of awareness about career opportunities in the blue economy, and the absence of a culture of ocean literacy (European Commission (EC), 2025). In addition, knowledge gaps have been identified among BB stakeholders regarding their legal responsibilities related to access and benefit-sharing, the use of genetic resources, and compliance with international and EU regulations (Schneider et al., 2022), which are often considered too complex and time-consuming (Schneider et al., 2023).

With this article, we aim to examine how BB education in Europe supports the (Blue) Bioeconomy Strategy, identify areas that still need improvement, and provide suggested actions to address the identified knowledge and capability gaps.

2 Policy and skills needed in relation to blue biotechnology

Various strategies and documents such as the Sustainable Development Goals (SDGs) and the 2030 Agenda for Sustainable Development (United Nations (UN), 2015), the Blue Economy Strategy (COM, 2021), the EU Bioeconomy Strategy (COM, 2025), the European Green Deal (COM, 2019), the circular bio-society by 2050 (BIC, 2019), as well as the national strategies and regulations of Member States highlights the role of education.

Additionally, according to the Agenda 2030 for Sustainable Development (United Nations (UN), 2015), one of the goals is to ensure that everyone has access to inclusive and equitable quality education and lifelong learning opportunities (SDG Goal 4). By 2030, it is aimed that all learners will acquire the knowledge and skills necessary for sustainable development, including education on sustainable practices and lifestyles. As part of SDG Goal 14, which targets the responsible conservation and use of oceans, seas, and marine resources, BB provides sustainable growth options for local communities (Vierros and De Fontaubert, 2017) by improving scientific knowledge, fostering research skills, and disseminating marine technology.

SDG Goal 4 is interconnected with other goals and aligns with SDG Goal 8, which promotes sustainable economic growth, full employment, and decent work for all. Youth entrepreneurship is considered important for boosting the economy. To achieve this, it is important to incorporate entrepreneurship and innovation into educational programs as viable career paths. For example, the partnership between the University of British Columbia (UBC) and the University of Papua New Guinea (UPNG) resulted in the isolation of a marine natural product from a sponge with anticancer properties, which subsequently entered the drug development process. This collaboration resulted in royalty payments that enabled UPNG to enhance its facilities and transfer knowledge from UBC (Vierros et al., 2016).

Several EU policy documents indirectly emphasise the importance of education and expertise in the BB field. The EU Bioeconomy Strategy (European Commission, 2025) aims to create jobs, particularly in coastal and rural areas, by involving primary producers in local bioeconomies. Having educated and skilled personnel is important for mobilising the potential of industry and innovation in these regions. Likewise, the European Green Deal (COM, 2019) places environmental sustainability at the heart of the European education policy reform (Zotti, 2022). A similar emphasis is reflected in the Vision for a Circular Bio-Society in 2050, shaped by the combined efforts of the Bio-based Industries Consortium (BIC), the Circular Bio-based Europe Joint Undertaking (CBE JU) advisory bodies, and fifteen industry associations (BIC, 2019). This vision aims to advance the bio-based industry, as well as to utilise leftover materials (waste, side streams) and leverage biotechnology in collaboration with other fields, creating job opportunities that require diverse skills. A central component of this vision is cooperation among industry and educational institutions to meet mutual needs for skills, capabilities and competencies. Indeed, it is fundamental that needs identified by companies are endorsed by and contribute to iterations of teaching programs. However, for this to take place, it entails that educational institutions and industry create closer collaborations and communication platforms. In several EU Member States and associated countries, national laws and strategies related to bio-based products are often linked to educational priorities, especially in the context of developing skills for a sustainable bioeconomy. EU Member States such as Ireland and Denmark, among others (Table 1), have dedicated plans or strategies for BB (Johnson et al., 2018), whereas others still lag behind.

Fragmented national policies and a lack of awareness and implementation of regulations such as the Nagoya Protocol (Schneider et al., 2023, 2022) prevent achieving sustainability in

TABLE 1 Classification of countries' engagement in blue biotechnology: A - countries with dedicated plans, programs, or strong policies, B - countries with considerable interest or activities, C - countries with some interest and activities, and D - countries with limited focus (adapted from Johnson et al., 2018 and on this research).

EU countries' engagement in BB			
A	B	C	D
Ireland	Belgium	Croatia	Bulgaria
Denmark	Finland	Cyprus	Estonia
Norway	the Netherlands	Malta	Latvia*
France*	Poland*	Iceland	Lithuania*
Germany	Greece	Romania	Ukraine
Spain*	Italy	Turkey	Austria
UK	Sweden		Switzerland
	Portugal*		
	Slovenia		

Countries where our study performed secondary school surveys on blue biotechnology awareness are indicated with an asterisk (*); more details are provided in section 4.

the blue economy. The Convention on Biological Diversity (CBD) (Secretariat of the Convention on Biological Diversity, 2016) and its protocols Nagoya (ICCROM, 2016) and Cartagena (Secretariat of the Convention on Biological Diversity, 2000) play a central role in shaping how marine genetic resources, associated traditional knowledge, and biotechnological innovations are assessed and used globally. The Nagoya Protocol (ICCROM, 2016) regulates access to genetic resources and the fair and equitable sharing of benefits, preventing biopiracy and ensuring that research and commercial use are based on legally obtained biological material and knowledge. This has direct implications for BB, where accessing marine microorganisms, extremophiles, and genetic resources from indigenous communities requires compliance with Access and Benefit-Sharing (ABS) procedures that may increase administrative complexity and costs, particularly for SMEs and public research institutions (Beck, 2019).

The Cartagena Protocol (Secretariat of the Convention on Biological Diversity, 2000) addresses biosafety issues related to living modified organisms. While it has had a regulatory impact on green biotechnology (agriculture) by ensuring the safe handling, transport and use of genetically modified organisms, resulting in their limited uptake in Europe (Falkner, 2000), it also affects BB. Research, environmental release, and industrial-scale biotechnological production of genetically modified microalgae, bacteria, or marine organisms must comply with safety, traceability, and risk-assessment procedures. These requirements, though intended to protect ecosystems and human health, may slow innovation and technology transfer, especially in jurisdictions where regulatory interpretation is restrictive, such as in Europe (Eckerstorfer et al., 2025).

Another issue that faces the European BB, and in general, its bioeconomy, is the lack of regulatory clarity regarding New Genomic Techniques (NGTs). Until now, NGT products fall under the EU Genetically Modified Organisms (GMO) regulation, which impedes EU biotechnology innovation for making bio-based solutions affordable, competitive and deployable at an industrial scale as stated in the European Bioeconomy Strategy vision. Moreover, this NGT regulatory instability causes the EU to lag behind the USA, China, Japan, the UK and other countries (Gallego et al., 2025).

The recently adopted Biodiversity Beyond National Jurisdiction (United Nations, 2023) relates to the conservation and sustainable use of marine biodiversity in Areas Beyond National Jurisdiction (Rochette et al., 2014). Its implementation is essential for BB, as many commercially valuable marine microorganisms originate from international waters. Understanding these frameworks is therefore crucial for researchers, industry, and policymakers to support ethical innovation while navigating legal and operational constraints.

There is also a skills gap in the blue economy and bioeconomy sectors between the demand for generalist and specialist knowledge of marine organisms' biology and taxonomy, as well as marine natural products chemistry, on the one hand, and the skills provided by higher education and vocational training on the other (Deloitte, empirica, and Fondazione Giacomo Brodolini, 2022; European Marine Board (EMB), 2017). A survey by the BBMBC project (Blue Biotechnology Master for a Blue Career; more information is available in section 3.8) revealed that industries valued the general skills of MSc-level staff more highly than scientific or technical skills (Table 2). The capability to acquire new skills, knowledge, and techniques was considered the most important (Desbois et al., 2019). This indicates the need to bridge existing skill and knowledge gaps while promoting responsible innovation and sustainable practices in BB, supported by standardised policies and regulations across EU Member States.

TABLE 2 Essential skills for master-level staff in the blue biotechnology and aquaculture industry (adapted from Desbois et al., 2019).

Scientific skills (in priority order)	General skills (in priority order)
Experimental design and research methodologies	Able to acquire new skills, knowledge and techniques
Knowledge of funding opportunities and procedures, including the sustainability assessment and legal framework compliance	Able to communicate effectively with colleagues, sponsors, and authorities
Culture of marine microorganisms, e.g., algae and bacteria	Able to use basic software packages and AI-based tools
Metabolite characterisation and advanced analytical, natural products and genomic approaches	Able to work in a multidisciplinary team.
Bioprocess engineering and scaling-up	Able to work independently with little or no supervision
Knowledge transfer to industry	Able to prepare written reports, patents and other documents

3 Blue biotechnology education in universities and other outreach programs in Europe

The mapping of BB educational activities in Europe was conducted using two complementary sources: (i) publicly available online information on BB study programs, training activities, and outreach initiatives, and (ii) a survey within the COST Action CA18238 Ocean4Biotech. To identify BB educational activities, we adopted the following inclusion criteria: programs were considered relevant when (1) they explicitly referenced blue or marine biotechnology in their title or curriculum, (2) they incorporated biotechnology tools or research focused on marine organisms, genetics, or marine bioresources, or (3) they were recognised EU-supported joint programs developed to advance BB competencies. Programs or activities that addressed marine biology, ecology, oceanography, or environmental science without biotechnological elements were excluded.

Based on our research data, we have identified numerous educational activities in at least 14 countries that emphasise BB. Specifically, we found 9 European countries located by the sea that offer dedicated study programs in BB (Supplementary Table S1). Among these, 2 are undergraduate study programs, and 9 are MSc-level programs. For detailed information, see Supplementary Table S1 and Figure 1.

The available data show the geographic and structural diversity of the BB education activities across Europe, with Western and Southern European countries, such as France, Spain, and Portugal, exhibiting more extensive educational initiatives in this field (Figure 1; Supplementary Table S1). Some countries, such as Poland and Lithuania, demonstrate strong engagement in BB education activities, particularly at the postgraduate level. Northern and some parts of Central and Eastern Europe have less educational activity, which might indicate that many programs are part of broader academic offerings rather than standalone degree programs. Initiatives, such as workshops and training programs, play an important role in the education of BB; their number is the highest among the surveyed countries (Figure 1, brown). The focus on MSc-level education and the expanding role of non-formal initiatives demonstrate that, while progress is being made, there is still a need for further development and coordination to improve access and integration, especially at earlier education stages and in underrepresented regions. It also indicates that standardising educational programs and strengthening cross-border education could contribute to a more coherent and integrated European BB education system.

There has been a rise in MSc programs at the national and international levels supported by EU funding mechanisms, such as Erasmus Mundus, in recent years. The BB subjects are also part of some MSc programs in marine ecology or biology, but surprisingly, not in organic chemistry or analytical chemistry. There is a trend of marine BB or MSc programs that are an output of EU projects. One example is the Master in Applied Blue Biotechnology program, developed under the BBMBC project in 2017 (see Section 3.8), which was partly replaced by the EU-CONEXUS joint MSc program in Marine Biotechnology under the Erasmus Mundus program in 2022 (https://www.eu-conexus.eu/en/marinebiotech-

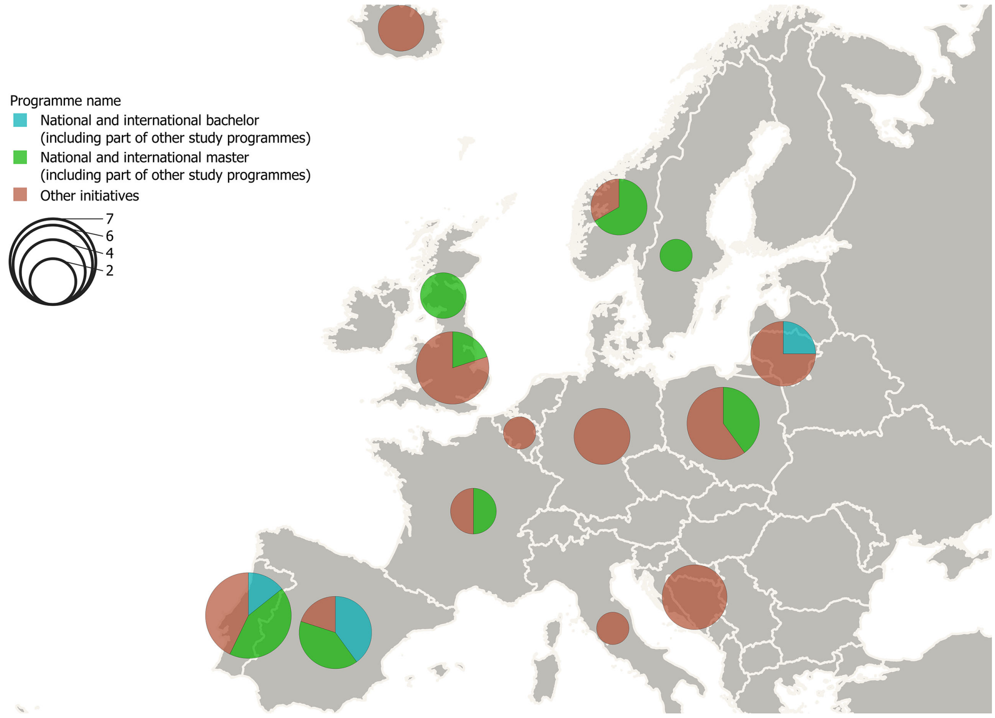

FIGURE 1
The distribution of blue education activities across Europe. The map uses different colored dots to represent master's programs (MSc, green), bachelor's programs (blue), and other initiatives (brown). The size of the dots corresponds to the respective number of activities. The data for this map is sourced from Supplementary Table S1.

structure/). A similar example is Erasmus Mundus Master of Science in Marine Biodiversity and Conservation, which started in 2010 and later the International Master of Science in Marine Biodiversity and Conservation (EMBC+) was developed from it. This programe is organised by 11 European universities in marine sciences as part of the Erasmus Mundus program (IMBRSea, 2025). This program prepares students for the blue bioeconomy's needs, with a focus on the sustainable use of marine biological resources and specialisation in BB.

However, the sustainability and financing of such studies remain a concern, particularly in terms of preserving the knowledge generated and ensuring the long-term continuity of these educational programs (Rotter et al., 2023).

BB is becoming part of other programs or initiatives more often (e.g., summer schools or training courses in collaboration with industry or dedicated to blue bioeconomy professionals), which are organised within research collaborations (projects and similar) and have a limited duration. However, we could identify only one online course explicitly dedicated to BBE, produced by the Interreg South Baltic Programe FOCUS project consortium (Udemy, 2025).

To gain insight into the challenges various countries face and the choices they make to realise their national objectives regarding the implementation of the Blue Growth Strategy and BBE, we compare several countries that differ in their engagement in BB, as defined by Johnson et al. (2018) (Table 1). All partners of the COST Action CA18238 Ocean4Biotech consortium were approached. However, only the national cases for which sufficient and verifiable information on BBE activities was provided were included. Consequently, the scope of representation is determined solely by the availability of publicly accessible information and the input received from COST Action members, and should not be interpreted as a deliberate omission of any country. Additionally, we explore ongoing study programs exclusively centred on BB, those initiated within the past years, and their associated challenges.

3.1 Blue biotechnology education in Poland - background, current status, and prospects

Poland is one of the few countries in Europe that does not have a national strategy for developing BB *sensu stricto* (Andrzejewska-Górecka et al., 2020). While the Government Biomedical Sector Development Plan for 2022–2031 indicates financial support for innovative medical biotechnology projects, biotechnology as a whole is not specifically mentioned in the National Reconstruction Plan aimed at recovering from the COVID-19 crisis (Gov.pl, 2021).

The biotechnology sector has faced numerous obstacles for years, including a shortage of financial capital, a limited number of skilled professionals, and administrative challenges, which have made Poland a latecomer in the European biotechnology race (Szczygielski et al., 2022). The lack of harmonised EU-level regulations may also have been a contributing factor. In addition, the regulatory status of biotechnology as a scientific discipline has fluctuated over time. After its temporary removal from the national classification system in 2018, biotechnology was reinstated in 2022 and, since the 2025 update, has been formally located within the field of Natural and Applied Sciences (Minister of Science and Higher Education, 2018; Minister of Education and Science, 2022; Minister of Education and Science, 2025). Despite these challenges, Polish universities have offered biotechnology education for almost 35 years, across medical, agricultural and technological institutions, providing BSc, MSc and PhD programs covering the full spectrum of biotechnological specialisations.

BB research and development primarily takes place in the cities of northern Poland, including the Tricity agglomeration of Gdańsk, Sopot, and Gdynia, Szczecin, and Olsztyn. Education in BB is provided to some extent through individual lectures and laboratories within BSc and MSc courses related to Ichthyology and Aquaculture, Aquaculture-Business-Technology, Exploitation of Natural Resources, and Oceanography (Supplementary Table S1).

Based on data from higher education institutions under the supervision of the Minister of Science and Higher Education in Poland, the biotechnology courses began gaining popularity in the 2019/2020 academic year. At least 8,000 students opted for these courses, which accounted for around 2% of all BSc and MSc students in the country. The percentage of students choosing biotechnology as their field of study has gradually increased, and in the 2021/2022 academic year, biotechnology ranked 12th among the most frequently selected fields of study, with 2.4% of prospective students choosing it (Ministry of Science and Higher Education, 2024). Although the University of Gdańsk introduced a BB specialisation under the Oceanography master's course at the Faculty of Oceanography and Geography during the academic year 2016/2017, the specialisation was opened only once (with 8 students) and closed after a few years due to not meeting the minimum number of applicants.

The lack of interest in BB appears to be influenced by students' primary motivations when choosing an MSc in oceanography, as most are interested in marine conservation, biology, and ecology of higher organisms. To address this, a new Marine Biotechnology MSc course was launched in the academic year of 2023/2024 in the Intercollegiate Faculty of Biotechnology jointly by the University of Gdańsk and the Medical University of Gdańsk. The course is tuition-free, and the entire curriculum is delivered in English. Despite this, enrolment in the first two years was low: only 14–15 students (half of the available places), including only a few people from outside Poland (Belarus, Nigeria, Ethiopia, Pakistan, India, Malaysia). Though small in size, the group comprises carefully selected individuals who are intensely focused on career opportunities in the BB sector. This dedication bodes well for the sector's development in Poland and enhances the public relations profile of the discussed course. In the 2025/2026 academic year, the University of Gdańsk, in collaboration with other partner institutions within the SEA-EU consortium (The European University of the Seas), has launched a new bachelor's degree program entitled Joint Bachelor in Sustainable Blue Economy (SeaBluE). One of the program's specialisation tracks is dedicated to the Conservation and Sustainable Use of Marine Resources (Supplementary Table S1).

In addition to academic initiatives, complementary efforts have also been undertaken to stimulate future interest and engagement among students. The outcome of the Blue Generation project in Poland was the engagement of 1, 501 students in the events organised at 26 institutions across the country. Eighty per cent of respondents felt that coastal tourism was the most interesting sector in the blue economy. The next sectors were as follows: maritime transport (50%), marine aquaculture and biotechnology (40%), ocean energy (30%), and shipbuilding (20%) (students were able to select three sectors). Additionally, by 31 December 2021, 305 people had participated in free career counselling and mentoring sessions, during which qualified career counsellors helped them develop their future careers, particularly in one of the sectors of the blue economy.

3.2 Blue biotechnology education links with regional strategies in Lithuania

Lithuania has strong and continuously developing competencies in medicine and industrial biotechnology, with an impressive annual growth rate of 25% over the past decade (TechFusion, 2025), making the potential for BB evident. The Life Sciences Sector Roadmap has been prepared (EIMIN, 2023). Life sciences already account for about 2.6% of Lithuania's GDP, and with targeted investment, the country aims to nearly double that figure, reaching 5% by 2030 (Invest Lithuania, 2025). The Lithuanian Bioeconomy Hub (bottom-up approach) started in 2024 and aims to integrate bioeconomy into national planning and foster cross-sector collaboration across Lithuania. Thus, at the strategic and political levels, there is a favourable context for the development of BB, although there are no specifically dedicated national policies for BB development.

Klaipėda, the third-largest city and the only port town in Lithuania, places a strong emphasis on the BBE, with a particular focus on aquaculture and BB. This strategic direction is outlined in the Klaipėda 2030: Economic Development Strategy (Klaipėda City Municipality, n.d.) and the Klaipėda Region Specialisation Strategy 2030 (Klaipėda Region Development Council, 2021) for the Lithuanian coastal area, including 7 municipalities. Klaipėda University (KU), being a specialised marine university in the region, plays a crucial role in implementing these ambitious strategic blue goals. Within KU, one of the new strategic science directions is "Towards sustainable technologies, blue and green growth, and a healthy sea", with a specific priority on Sustainable management of marine resources through the development of aquaculture and BB. This priority covers all education levels, from lower secondary (as part of the STEM non-formal high school education program) to lifelong education. Moreover, one of the tasks of the recent national project dedicated to universities to support excellence in KU is to create an internationally integrated center of excellence, bringing together scientists and infrastructure working in the areas of sustainable coastal development, who would be able to respond to economic and social challenges and ensure the provision of science-based knowledge and solutions for the development of coastal regions.

In line with the strategic regional goals, KU has developed an updated bachelor's study program in Biology and Marine Biotechnology. This program focuses on aquatic biological systems and resources, as well as their innovative management and applications. The curriculum was updated in 2019 to align with regional strategic development directions and meet the high demand for applied biology studies among students. The new BB-oriented study program has gained significant attention, with a growing number of students enrolling each year (Supplementary Table S1).

For professionals and stakeholders interested in, or already working in, the blue economy and related sectors, KU first established the Blue Growth Leaders Academy, which was later expanded within the EU-CONEXUS European University alliance. This international, non-degree training program enables participants (from businesses, local authorities, and educational institutions) to connect with leading experts and engage in a networking platform dedicated to blue growth. The program includes a variety of blue topics, including BB. Overall, KU and its partners aim to ensure the sustainable growth of the blue bioeconomy in Lithuania.

3.3 Blue biotechnology education in Slovenia

Despite having a short coastline, just short of 50 km, Slovenia's strategic geopolitical location and its natural resources offer suitable conditions for establishing novel research fields and collaborations. Indeed, the blue economy has been included as a horizontal topic in the recent (2021) iteration of the Slovenian Smart Specialisation Strategy, S5 (Slovenian Sustainable Smart Specialisation Strategy), thereby acknowledging its importance from both a legislative and economic perspective. In the BB sector, there is one Research Programe "Marine and microbial biotechnology", funded by the Slovenian Research and Innovation Agency, that is primarily devoted to BB, which enables the education of the personnel involved in its participating organisations (National Institute of Biology, Jožef Stefan Institute, Biotechnical Faculty within the University of Ljubljana), mainly through the programe for training of PhD students. These and several other organisations also support the development of BB through various national, regional and international projects, often establishing co-creation and learning clusters. Such cooperation networks can include business clusters, research institutes and companies, allowing the sharing of knowledge on the extraction of different compounds of various marine organisms and serving as platforms for discussion of the applicability of these compounds in different products, thus enabling further development of the field in the region and beyond (Doussineau, 2020).

The development of BB in Slovenia is also enabled by involvement in local (e.g., Fisheries local action group - LASR Feral), national (e.g., BLUEWARE Slovenia), regional (MASBBE - Maritime Sustainable Blue Economy S3 community of practice within the European Commission), and European (Ocean4Biotech - chairing) science and innovation clusters. However, most of these are not financially supported by governmental or other funds (one exception is the Fisheries local action group), hence participation in them is restricted to an (often) voluntary basis.

Currently, there are no BB-specialised undergraduate or postgraduate studies. Knowledge is obtained through specialised lessons, training, summer schools, and workshops, typically restricted to the duration of financed projects.

3.4 Blue biotechnology education in Croatia

The Adriatic Sea's coastal systems harbour many bio-based products with potential for novel medical and biotechnology applications. BBE in Croatia is growing through university degrees, vocational training, and online courses. Croatian universities recognise the significance of BB and have incorporated it into their academic programs. For example, the University of Split and the University of Dubrovnik collaborate on an MSc program in Marine Biology and Ecology, and offer a doctoral program in Applied Marine Sciences. This includes courses on BB that focus on the sustainable use of marine resources. Similarly, the University of Zagreb has introduced a program in biotechnology with a focus on marine applications, covering topics such as bioinformatics and bioprospecting. The University of Zadar, in collaboration with partners from the EU CONEXUS alliance, offers the aforementioned two-year joint MSc program in marine biotechnology.

Croatia aims to improve skills related to modern, environmentally friendly production and aquaculture practices (Edmeades et al., 2021), as well as the use of digital technologies. For example, recent initiatives under the uBlueTec project (uBlueTec, 2023) are dedicated to developing a training framework combining green, blue, and digital skills. To meet the needs of the blue economy, curricula are planned to be developed in collaboration between universities, vocational education providers, and SMEs. Various educational institutions in Croatia offer courses, modules, and studies on aquaculture or run projects in this area; however, the education in this field remains scattered and often lacks innovative methods (Edmeades et al., 2021).

The Croatian Initiative in BB has created a solid base for incorporating BB into the country's education system. This initiative resulted in the creation of the Center of Excellence for Marine Bioprospecting, BioProCro (IRB, 2025). This interdisciplinary center brings together experts from institutions such as the Ruđer Bošković Institute, University of Split (Faculty of Chemistry and Technology), University of Zagreb (Faculty of Food Technology and Biotechnology), University of Rijeka (Department of Biotechnology), and University of Osijek (Faculty of Food Technology). The BioProCro Center unites internationally acclaimed research groups working in biotechnology, chemistry, pharmacology, microbiology, process engineering, and ecology.

3.5 STEM in Bosnia and Herzegovina

To the best of our knowledge, there are no BBE activities in Bosnia and Herzegovina (BIH). However, the existing STEM initiatives could serve as a starting point for implementing BBE.

The educational project ENABLE BIH: Enhancing and Advancing Basic Learning and Education in BIH was implemented from 2016 to 2020 and organised by Save the Children International, with financial support from the United States Agency for International Development (USAID). With the general purpose of contributing to improving learning outcomes in primary and secondary schools in BIH, this was the first project to introduce STEM activities in formal education institutions in the Western Balkans. During Phase 1 (2016-2018), a policy framework for STEM/PPDM (Pedagogy, Psychology, Didactics, and Teaching Methods) was established through the development of key documents (Avdispahić, et al.., 2018a; 2018b, 2018c; Lukić Bilela and Muratović, 2018; Maksimović, 2018; Mrdović, 2018; Tanović, 2018; Feden et al., 2018a, 2018b, 2018c). Phase 2 (2019-2020) of the project focused on implementation in STEM/PPDM through several activities, mainly: training for STEM/PPDM trainers, equipping 12 model schools and 3 university laboratories and establishing cooperation with the business sector to provide students opportunities to gain practical experience that is important for the labor market (Supplementary Table 4).

Over the four years, the ENABLE BIH project involved representatives from universities, Ministries/Departments of Education, pedagogical institutes, primary and secondary school teachers, as well as domestic and international experts. Almost 300 educators completed training to implement the STEM curriculum in their teaching. At the same time, 2, 556 primary and secondary school students received access to quality STEM education. Of these, 1, 252 were females and 1, 304 were males, indicating that the ENABLE project has made progress toward equal gender representation in science and technology. Many of these young students have found their future professional advancement thanks to the ENABLE project.

To provide quality education for primary and secondary school teachers and to improve vertical integration across all levels of education, cooperation has been established with three faculties of natural sciences and mathematics in BIH: the University of Sarajevo, the University of Banja Luka, and the University of Mostar. The project funded the set-up of STEM laboratories in 12 model schools, while the mentioned faculties were also equipped with STEM laboratories established as Centers of Excellence. During the 2018/2019 school year, STEM lessons integrated into the regular teaching process covered approximately 25 percent of the regular education process (ENABLE_BIH: ANNUAL NARRATIVE REPORT, 2020; Catalog of Best STEM Practice, 2020; MEASURE-BIH, 2018).

3.6 Blue biotechnology education in Portugal

In Portugal, data retrieved from the Ministry of Science and Education (DGES, 2025a) in 2022 indicate that university studies are primarily focused on well-established scientific fields, but there is a lack of sufficient disciplinary integration of BB. While there are degrees in Chemistry, Chemical Engineering, Biochemistry, Marine Sciences, Integrated Oceans Studies, Marine Biology, and Aquatic Environmental Sciences, there are no dedicated degrees in BB. The same is observed at the MSc's degree level, where existing programs focus on biotechnology, biochemistry, aquatic biological resources, and marine sciences, but do not offer specialised degrees in BB (DGES, 2025b).

Some initiatives represent a step towards addressing the gaps in specialised education in BB. Leiria Polytechnic Institute is offering a degree in Marine Biology and Biotechnology, along with an MSc program in Marine Resources Biotechnology (Supplementary Table S1). A doctoral program in BB, called "Marine Biotechnology and Aquaculture", has been implemented by the University of Minho and the University of Porto since 2022 (Supplementary Table S1). However, despite this promising start, basic training in areas such as organic chemistry, marine natural products chemistry; analytical chemistry; mass spectrometry; nuclear magnetic resonance (NMR) spectroscopy; genomics; and synthetic biology — all subjects essential for the successful discovery of marine natural products — is still needed (Gaudêncio et al., 2023) and is not well covered in BB courses at any level of university education. In Portugal, all Master's and PhD programes are currently undergoing a new accreditation cycle overseen by the Agência de Avaliação e Acreditação do Ensino Superior (A3ES), a process that is expected to lead to curricular revisions, strengthened research capacity, enhanced internationalization, and overall improvements in BB academic courses and institutional standards.

Although BB is gradually finding its place in Portugal's education system, there is still a noticeable gap in specialised programs, especially at the MSc and PhD levels. That said, when compared to other countries examined in the case studies, Portugal stands out for offering a relatively wide range of academic programs in this field.

3.7 Cyprus and blue biotechnology: position, potential, and strategic outlook

In coastal Cyprus, there is currently no standalone national strategy specifically dedicated to BB. The BB development and equal distribution of benefits from genetic resources are part of Cyprus's broader Integrated Maritime Policy (IMP) and Maritime Spatial Planning (MSP) frameworks (Shipping Deputy Ministry, 2021).

A central pillar of Cyprus's blue innovation agenda is the Cyprus Marine and Maritime Institute (CMMI), established with support from Horizon 2020 under the "MaRITeC-X" Centre of Excellence program (CORDIS, 2017). The CMMI functions as a hub for research and innovation in marine sciences, including BB, with ongoing work on marine bioresources such as algae and marine microbes, and biomass applications for pharmaceuticals, biofuels, and aquaculture (CMMI, 2016).

Cyprus also participates in regional and EU-level marine research initiatives. Notably, it contributed to the BLUEMED initiative and led the MEDALGAE project, which explored the cultivation of microalgae for the production of bio-based high-value compounds (MedAlgae, 2016). Through the Sustainable Blue Economy Partnership under Horizon Europe, Cyprus co-funds transnational research calls in areas such as climate-resilient aquaculture and biotechnology-based marine value chains (Bluepartnership, 2025).

While these initiatives reflect increasing capacity, no dedicated national research or higher education program in BB currently exists in Cyprus. However, academic training and marine expertise are expanding. The University of Cyprus and the Cyprus University of Technology offer programs in marine science, shipping, and aquaculture. The latter is establishing a new School of Marine Sciences in Larnaca, which will integrate sustainability, biotechnology, and ocean innovation (Cyprus University of Technology, 2025). Research institutions such as the CMMI, in partnership with academia and industry, offer applied research and technical training aligned with BB objectives.

To support workforce development, the Human Resource Development Authority (HRDA) of Cyprus has included blue economy skill needs in its national labour forecasts. It is anticipated that by 2026, approximately 10% of national employment will be related to blue sectors, with biotechnology highlighted as a high-potential field (Human Resource Development Authority (HRDA), 2016). Furthermore, Cyprus is hosting the new Commonwealth Blue Charter Centre of Excellence in Larnaca, which will contribute to marine conservation, governance, and aquaculture, as well as potentially building skills in biotechnology (Commonwealth, 2024).

In conclusion, Cyprus is gradually incorporating BB into its national innovation and economic plans, even as part of broader marine and maritime strategies. Although there is still no dedicated national program, institutional capacity and research participation in EU frameworks are on the rise. Strategic investment in focused education, research infrastructure, and cross-sectoral partnerships will be essential to positioning Cyprus as a regional actor in the European Blue Bioeconomy.

3.8 An international master's program outcome of the project "The Blue Biotechnology Master for a Blue Career"

The Blue Biotechnology Master for a Blue Career (BBMBC) was funded by the European Maritime and Fisheries Fund Work Programe. It was a collaborative effort led by teams of academics from the University of La Rochelle, Catholic University of Valencia, University of Stirling, CIIMAR, and industrialists from various BB companies.

To ensure the program's significance and effectiveness, relevant sectors and companies across the EU were initially identified. Private sector partners actively participated in all stages of the BBMBC project, including program design and teaching. One-on-one meetings were also organised, and project members attended professional and scientific gatherings across the EU to connect with representatives from various companies.

Specific interviews took place with key institutions, such as the Federation of Agrifood Companies in Spain, to obtain further input. Targeted events, such as the "Blue Days Meeting" at University of La Rochelle and "Challenges and Opportunities in Blue Biotechnology" at the Catholic University of Valencia, were organised to attract small and medium-sized enterprises (SMEs) and discuss the current skills gap in the sector. The information collected through these efforts was essential for designing the final MSc program curriculum. Feedback documents and assessment questionnaires were prepared, enabling companies to evaluate whether students had acquired the necessary skills.

The first Applied Blue Biotechnology Master II students were enrolled at the University of La Rochelle in September 2017. The program, spanning four months of teaching from September to December, focused on introducing scientific, technical, and knowledge-based skills. Following the teaching period, students underwent a six-month training period at an institution related to BB under the guidance of a mentor employee. To complete the program, students were required to produce an extensive written thesis and deliver an oral presentation, both of which were assessed by a panel of specialists. Overall, the BBMBC program and its suite of tools provided 34 MSc degrees with the skills and knowledge essential for careers in BB, particularly in the health, nutrition, and aquaculture sectors. The BBMBC project successfully developed an MSc program curriculum to address existing skill gaps in the BB sector, with the aim of meeting industry needs (BBMBC, 2023).

3.9 Joint master program in marine biotechnology within the EU-CONEXUS (European university consortium)

The European University for Smart Urban Coastal Sustainability (EU-CONEXUS) is a transnational European higher education and research institution that covers innovative urban sustainable coastal development from a global point of view (EU-CONEXUS, 2025). EU-CONEXUS is composed of six European universities located in France, Greece, Romania, Lithuania, Spain and Croatia, and three associated universities in Germany, Ireland, and Cyprus. The consortium aims to play a central role in promoting the blue economy and blue growth, and contribute to the skills and competencies of the graduates who can work in a complex and challenging labor market.

EU-CONEXUS partner universities have combined their strengths and know-how in an interdisciplinary joint Master's program in Marine Biotechnology (JMPMB), also offering students the opportunity to study at an international inter-university campus. Being a joint program, its main activities are executed jointly by the universities of the Consortium, including a joint diploma awarded by the participating higher education institutions, which is recognised as a joint degree in the higher education systems of the awarding institutions.

JMPMB's structure aligns with the BB pipeline (Figure 2) through 4 core thematic areas that provide a comprehensive biotechnology toolbox for prospecting the bio- and chemo-diversity of aquatic genetic resources and an approach to the BB business ecosystem. Specialisation tracks and individual professional practice (Internship), individual research (Academic Research Integration), and final thesis work allow students to tailor their study program to their aspirations.

JMPMB offers a wide range of mobility opportunities and ensures integration in groups and networks. Two mobilities are made for the whole group of students during the first and second semesters, and mobility is provided in small groups during the 3rd semester, with two additional mobilities for each student during the 2nd and 4th semesters.

A multidisciplinary approach is a core aim of the JMPMB because it is necessary from discovery to market launch. R&D activities consist of the participation of multidisciplinary teamwork from public research centers, universities, and private companies and are reinforced by the course Academic Research Integration (ARI) (Chirivella-Martorell, 2023). Thus, the ARI course aims to train students in professional skills related to scientific writing, project planning, management, and presentation of research proposals developed in multidisciplinary teamwork. ARI is developed during the 3rd semester while students are distributed across 6 universities and different specialisations. Students from various partner universities and/or several specialisations work together on a shared and transversal research project. They compete to choose research lines proposed by professors in the partner universities, where they develop laboratory skills through hands-on training and are practice-oriented, supervised by researchers. Then, students offer their expertise to their classmates to design a proposal for the multidisciplinary research project; these

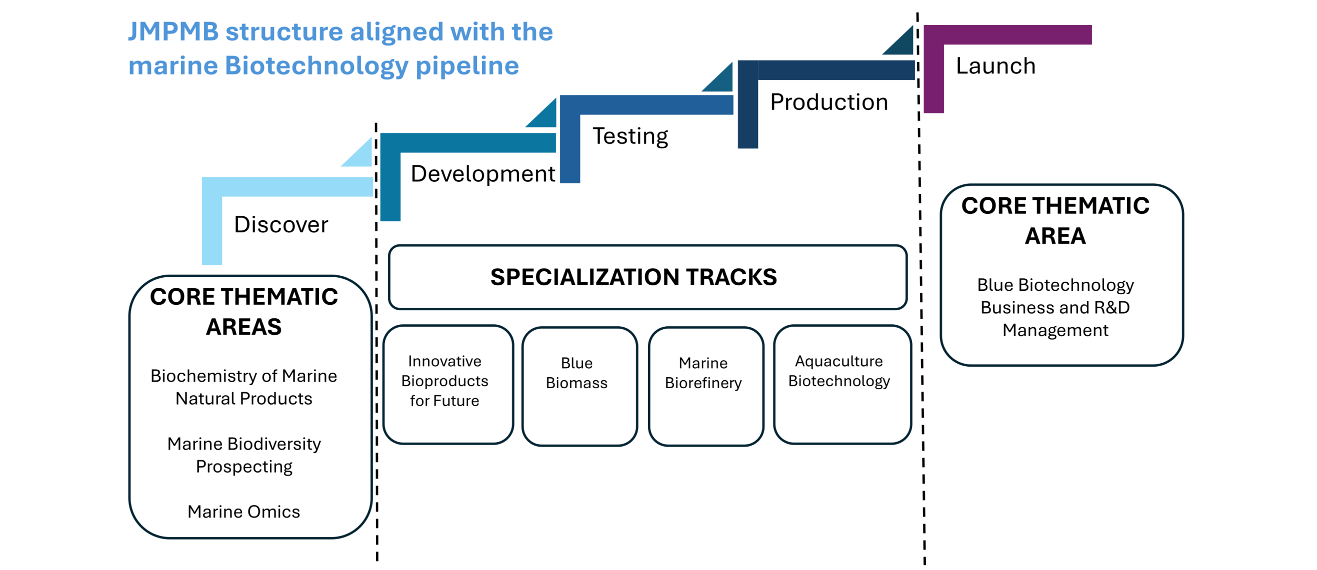

FIGURE 2
The JMPMB structure alignment with the Blue Biotechnology pipeline.

research lines become work packages of multidisciplinary research proposals that professors of the partner universities evaluate. The proposed multidisciplinary research projects allow the students to apply general academic, research and/or design practice skills. Each student participates in this multidisciplinary project, carrying out research activities related to their specialisation at one of the partner institutions. At the same time, transversality is encouraged through collaboration between students from different specialisations and in different locations, which adds to each student's work and enables a truly multidisciplinary joint research project. Every student works closely with his/her Academic Supervisor, who helps meet the project's milestones. All team members gain an interdisciplinary overview of the entire work because of their individual and collaborative work. Converging research lines from more than 20 researchers for JMPMB purposes creates an opportunity to boost multidisciplinary and transnational research groups on BB within the EU-CONEXUS community.

4 Blue biotechnology education at schools and ocean literacy

4.1 Survey on knowledge and interest in blue biotechnology by secondary school students

To understand the interest in BB among the future generation of BB experts, we prepared a survey in eleven languages (English, Polish, Lithuanian, Latvian, Portuguese, Croatian, Bosnian, Serbian, Turkish, French, and Spanish) and uploaded it to the EUSurvey platform. We targeted secondary school students by disseminating the survey through personal and professional contacts (mainly COST Action CA 18238 Ocean4Biotech members) and by asking secondary school principals and teachers to distribute it within their schools (Supplementary Table S2). The survey was conducted from October 1, 2021, to February 2, 2022, targeting individuals aged 15 to 18 years in the final years of secondary school. We received 936 responses from seven EU countries (Bosnia and Herzegovina, France, Latvia, Lithuania, Poland, Portugal, and Spain), with 62.8% female and 29.6% male participants (Supplementary Table S3). Due to the low number of responses (21), Bosnia and Herzegovina was excluded from further analysis. The low number of responses is most likely due to insufficient knowledge and/or interest in BBE, as it has not yet been introduced into the education system of Bosnia and Herzegovina.

Nearly half of the respondents (48%) demonstrated an understanding of what biotechnology is about; a similar proportion of females (50.35%) and males (46.96%). Additionally, there was a similar proportion related to the place of living (next to the sea or on the mainland, in cities or rural areas) of the corresponding country (45.17-60.6%). However, there were notable variations among countries ($p < 0.001$, Chi-square test). The highest awareness was recorded in France (76.2%), followed by Poland (68.64%), while Latvia had the lowest proportion, with only 25.2% of respondents demonstrating awareness (Figure 3).

In contrast, only a small proportion of respondents (18.1%) were familiar with BB ($p < 0.001$) compared to biotechnology. A higher percentage of students in France (36.5%) showed awareness of BB ($p < 0.01$), while the awareness was considerably lower in Spain, Lithuania and Latvia (16.1%, 7.2% and 11.4%, respectively) (Figure 3). Proportionally, a higher percentage of those who knew about biotechnology (29.09%) were considering BB as a potential option for studies than those who did not know about biotechnology (8.9%) ($p < 0.0001$). Similarly, among those who knew about BB, a larger proportion (34.2%) were considering it for

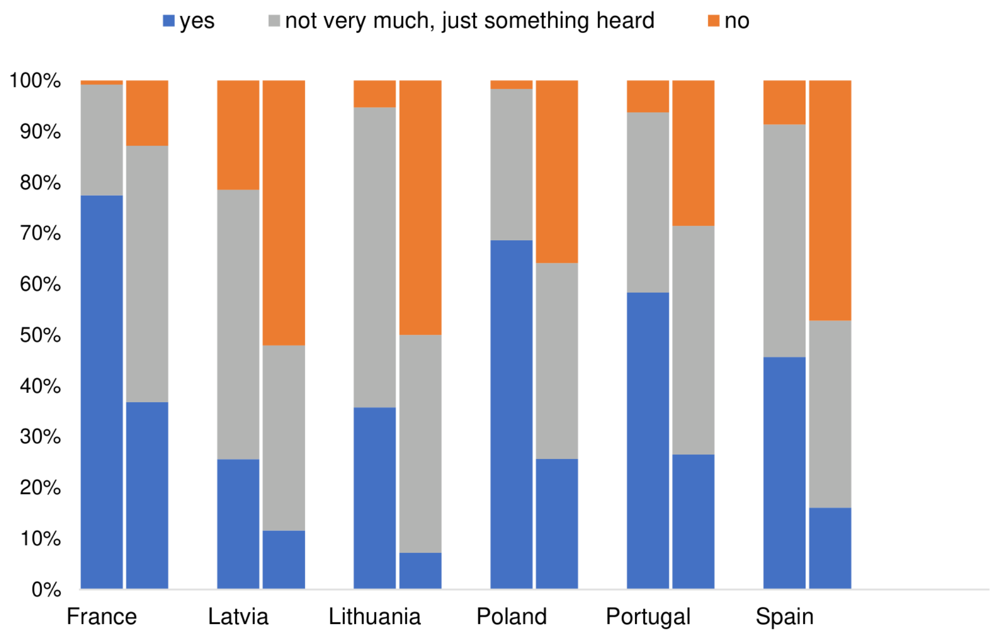

FIGURE 3
The proportion of secondary school students familiar with biotechnology (1st bar) and blue biotechnology (2nd bar).

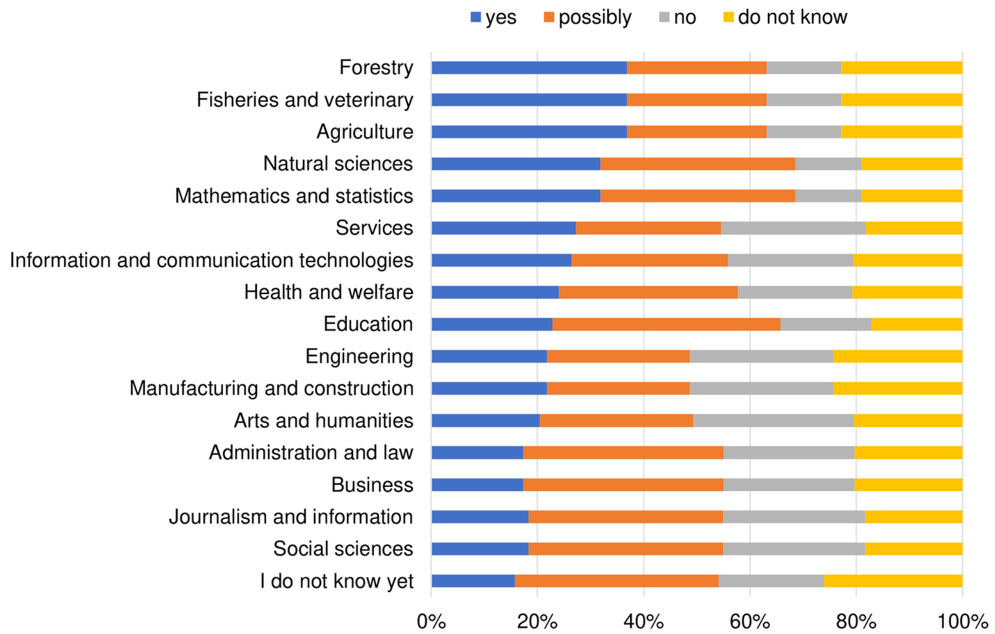

FIGURE 4
Interest in blue biotechnology among secondary school students based on intended study field. The distribution of responses ("yes", "possibly", "no", "do not know") regarding interest in blue biotechnology is expressed as percentages within each intended study field. Percentages are calculated per field and sum to 100%.

future studies than those who did not know about BB (16%) ($p < 0.001$).

A statistically significant relationship was found between students' planned field of study and their interest in BB ($p < 0.05$, Chi-square test). Students planning to study agriculture, forestry, fisheries, veterinary science, mathematics, statistics, or natural sciences showed greater interest in BB studies than other groups (Figure 4).

More specifically, students planning to study in natural or health science fields also showed significantly higher levels of interest in BB ($p < 0.01$). The highest interest was reported among those intending to pursue careers in oceanography/marine sciences, genetics and molecular biology, biotechnology, and ecology (Figure 5).

Around 9.4% of all respondents participated in STEM activities in addition to the regular school curriculum. Proportionally, more males (13.5%) participated in STEM compared to females (7%). A higher proportion of respondents from Latvia, Portugal, and Spain participated in STEM activities (12-13.8%) compared to those from France, Lithuania, and Poland (6-6.3%).

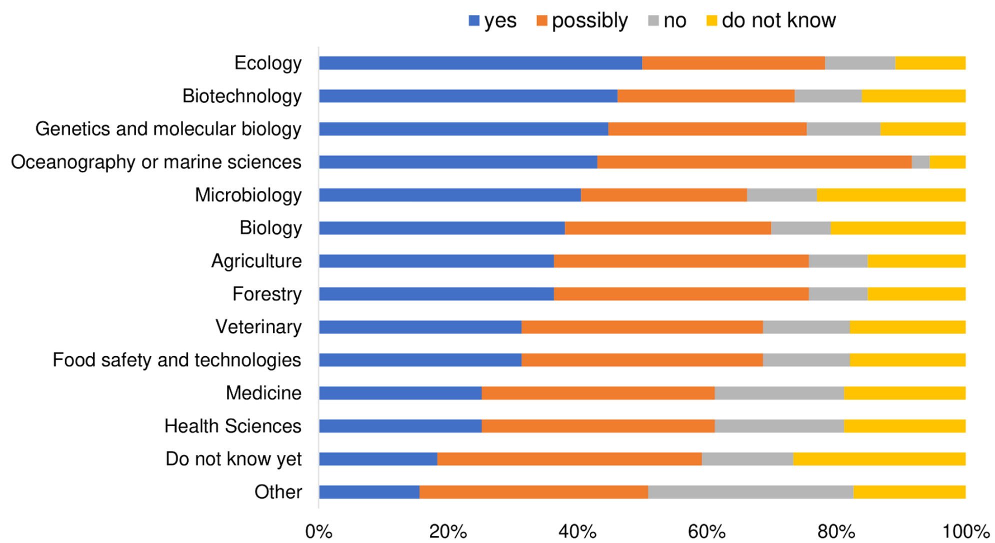

FIGURE 5
Interest in blue biotechnology among secondary school students based on intended study subject in natural or health science fields. The distribution of responses ("yes", "possibly", "no", "do not know") regarding interest in blue biotechnology is expressed as percentages within each intended study field. Percentages are calculated per field and sum to 100%.

Approximately 22.8% of all respondents expressed interest in pursuing studies related to BB. The involvement in STEM activities, in addition to the regular school curriculum, had only a slight impact on this interest. Among those involved in STEM, 35.7% expressed interest in BB, whereas among those not involved in STEM, the percentage was 21.6%. There was no difference based on gender (34.3% for females and 37.14% for males) or place of living in the country (ranging from 19% to 25%) (p = 0.435 and p = 0.961, respectively).

There were notable differences in the level of interest across countries, depending on students' involvement in STEM activities beyond the regular school curriculum. Among those not involved in STEM, interest in BB ranged from 14% in France to 30.6% in Portugal. For students engaged in STEM, the interest was higher, reaching 57.4% in Latvia and 50% in Portugal. In Lithuania, however, only 16.6% of students involved in STEM activities expressed interest in BB, and uncertainty was particularly high: 41.8% selected "do not know" when asked whether they would consider pursuing education in this field.

When different types of STEM activities were considered, the highest proportion of students interested in BB studies was among those involved in more than one activity (57.1%). Interest was also high among students engaged in activities not explicitly listed in the questionnaire, such as Erasmus projects, conferences, Olympiads, family-related activities, or other events. In addition, greater interest in BB was observed when STEM activities were organised at research institutes, private companies, or delivered as non-formal education within schools (Figure 6).

Thus, summarising the results, we see that the highest levels of interest in BB were observed among students interested in studying oceanography/marine sciences, genetics and molecular biology, biotechnology, and ecology. So, students already oriented toward life science and environmental disciplines are more open to engaging with BB as a potential career path, and this can be used as an opportunity to build targeted outreach and educational integration within these disciplines to strengthen future participation in the BB sector.

Additionally, involvement in STEM activities outside of regular school programs appears to influence this interest. Our survey also shows that knowledge and interest in BB studies differ across countries. Students from France and Spain have higher awareness of BB studies but lower interest. Those countries could improve their engagement by connecting BB with practical skills through action-oriented activities, providing a clear understanding of career opportunities, and demonstrating the relevance of societal challenges. Portugal and Poland are countries with high awareness and high interest in BB. They can benefit from advanced educational programs, opportunities to do internships and partnerships within the BB sector. Latvia and Lithuania are countries with low awareness and comparatively high interest; therefore, awareness-raising activities, curriculum improvement, or targeted teacher training related to BB could be highly effective in these regions.

4.2 Enhancing blue biotechnology education focuses on primary and secondary education levels

Based on our survey results and published literature on the targeted topic, one important aspect is that understanding of biotechnology differs between countries, and the way biotechnology is taught in secondary schools varies widely depending on the chosen program (Paš et al., 2019). Several studies have found that secondary school students have a limited understanding of biotechnologies in general (Alberro et al., 2023; Vanderschuren et al., 2010), and their interest in this field is closely related to their knowledge about it. Fundamental knowledge gaps, such as a lack of understanding in basic genetics, can make it difficult for pupils to understand more complex biotechnology topics (de la Hoz et al., 2022). Therefore, more effort should be devoted to improving this knowledge in secondary schools through formal or additional education, as well as investing more in teachers' training to equip them with modern, more engaging teaching methods (Alberro et al., 2023).

Previous research showed that universities and research institutions can help by organising non-formal activities, such as summer schools (Kataržytė et al., 2017), organisational/institutional open days, and science events (e.g., the European Researchers'

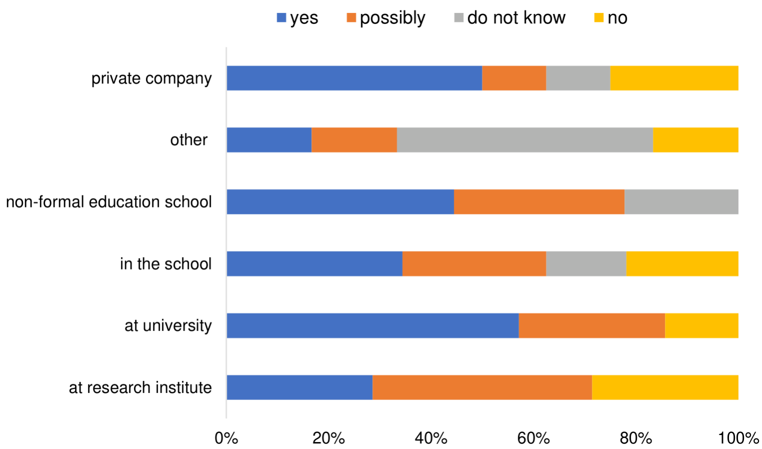

FIGURE 6
Interest in choosing blue biotechnology studies and gaining knowledge concerning the place of performance of STEM activity.

Night Program). Those activities can be important in building interest in marine research. For example, Portugal offers programs for young children and adolescents, such as the Blue School (Escola Azul, 2025) and Ciência Viva (2025), which aim to enhance ocean literacy (Costa and Faria, 2025). STEM fields are integral to addressing several current societal challenges, and science education in schools should focus on developing children's conceptual understanding of the marine environment and its importance for preservation (Andersson and Gullberg, 2014; Siry and Kremer, 2011).

Parents play a key role in shaping their children's views on the environment and sustainability (Sihvonen et al., 2024), while preschool education is important for the effective use of teaching methods. Early childhood science education at pre-primary and kindergarten levels (ISCED Level 0) plays an important role in supporting the physical, social, and cognitive development of young children (Larimore, 2020). Sundberg et al. (2016) found that the preschool community's structure and the nature of the educational culture within it were particularly significant in determining when and how children were given science learning opportunities. In communities characterised by insufficient commitment, a lack of understanding of learning outcomes and the purpose of activities, science education loses its meaning. However, a similar situation occurs in communities where science learning is not actively supported, despite an enthusiastic approach and a shared understanding of the science activities performed.

Promoting awareness and understanding of the ocean, its wildlife, and their potential for biotechnologies can be achieved through STEM or ocean literacy activities (Costa and Faria, 2025). Different approaches are being explored to bridge the gap between traditional STEM curricula and the needs of the Generation Z students, who tend to be less engaged by abstract, theory-based topics but show strong interest in STEM when it is connected to environmental and societal issues (Persano Adorno et al., 2021). Starting with current issues relevant to students, such as the social and environmental impacts of new technologies, and connecting STEM concepts to real-world technological solutions that address environmental challenges, may further increase their interest. It was found that knowledge of new STEM content makes students feel like active participants in technological innovation, bringing them closer to the STEM world and enabling them to make more informed choices for their future careers. Evidence from STEM education research shows that hands-on bioprocess learning can effectively bridge theoretical knowledge and practical application, indicating that such approaches could enhance early-stage BBE (Geuer et al., 2025). Another study found that fostering bioentrepreneurship among young graduates requires constant encouragement of innovation at every level, including schools and even preschools (Hossain and Tan, 2024). Curricula focused on BB topics could be incorporated into formal education by introducing topics into biology, chemistry, environmental science, and geography classes. However, when it comes to lifelong ocean education, the emphasis should shift towards non-formal and informal education, as these approaches centre on individual learning and development (Figure 7).

BB is rarely considered in the context of ocean science education and is mainly explored as part of marine prospecting, which could help develop products with unique features, such as resistance to heat and toxins (Scowcroft et al., 2019). As part of the ocean literacy assessment, it was found that secondary school students in Italy prioritise tourism, ocean and marine energy, and fisheries as the most important sectors of the blue economy, with only a few considering BB (Forleo and Bredice, 2024). Investing more effort in ocean literacy is crucial, as it connects students with

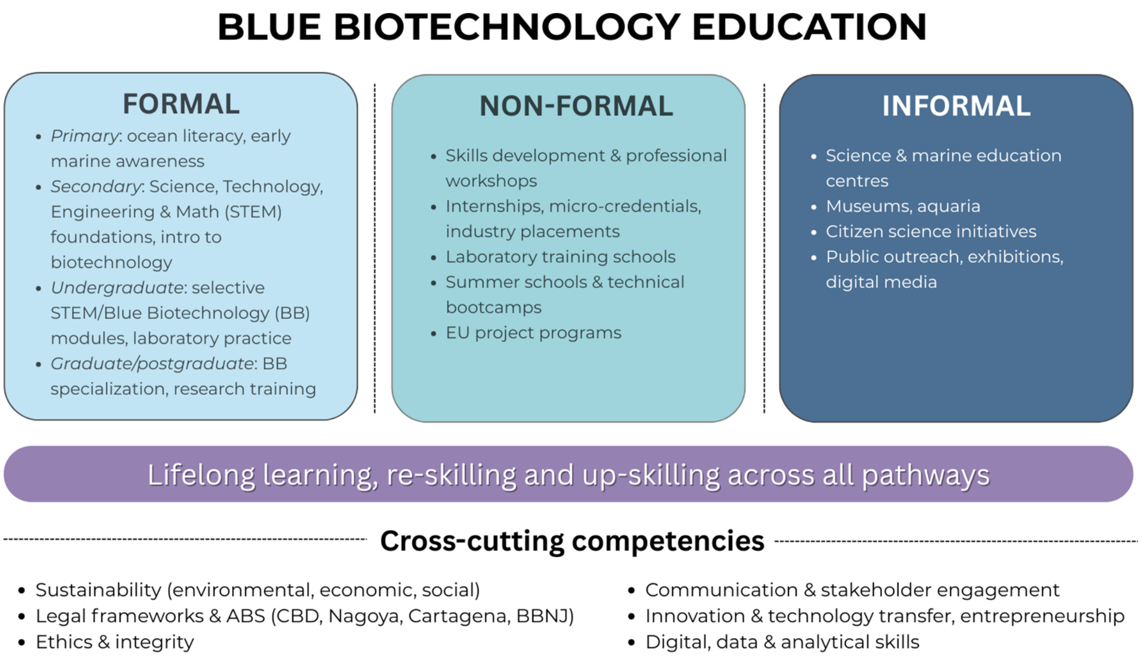

FIGURE 7
Blue biotechnology education framework.

marine environments and promotes the sustainable use of ocean resources (Cava et al., 2005). It can help understand the fundamental principles of ocean science and enable effective communication about marine issues, making responsible choices regarding marine resource use (Kelly et al., 2022). Including BBE in ocean literacy activities can demonstrate how marine resources can be used sustainably to create valuable products, while also promoting fair policies and the responsible use of ocean resources (Rotter et al., 2021).

In non-formal education, citizen science has recently been widely used in the marine field to raise public awareness of the ocean and to participate in scientific research (French et al., 2017; Kelly et al., 2022). While this approach has not been used for BBE yet, it has potential as a tool to raise awareness of the value of marine resources, for example, by conducting algal monitoring or exploring beneficial marine microbes.

Non-formal education in BBE often takes place within consortia that support the growth of small and medium-sized enterprises (SMEs). The SUBMARINER Network for Blue Growth EEIG, a leading network hub for the blue bioeconomy, promotes innovative and sustainable uses of marine resources in the Baltic Sea Region and beyond. This network promotes collaboration between universities and the blue sector by supporting recent graduates in acquiring transversal skills that complement their scientific knowledge, while also raising awareness among pupils and students about career opportunities within the marine and maritime sectors (Submariner, 2025).

Informal education is more individual-driven and includes self-directed, incidental, and tacit learning through socialisation (Schugurensky, 2000). It happens outside of formal and non-formal educational institutions. It can play a big role in increasing awareness about the dangers facing the ocean and the need for sustainable use of marine resources. Short ads that highlight endangered species, habitats, and interesting facts can be helpful in informal learning (Livingstone, 1999). Lifelong learning, whether through formal, non-formal, or informal ways, allows people to gain new knowledge, skills, and abilities related to biodiversity and the ocean. This can result in a well-informed, ocean-literate society where knowledge and ideas are shared to ensure sustainable marine development (Power and Maclean, 2013). Moreover, the key competencies acquired by the lifelong BB education should result in an understanding of 1) the importance of the ocean worldwide; 2) the important processes in the ocean and their interconnections; 3) the biopotential of marine resources; 4) the opportunities for bioprospecting; and 5) the importance of the BB for sustainable bioeconomy development.

4.3 Education as enabler for a responsible blue bioeconomy transition

The transition toward a sustainable blue bioeconomy requires more than technological progress — it depends on informed and empowered stakeholders. Both the food industry and consumers remain key actors whose engagement and understanding determine the societal legitimacy of new biotechnologies. Yet, as demonstrated in the EU-funded project GeneBEcon, which focused on NGTs in microalgae among other initiatives, the Transition Action Plan (TAP) for the Food Industry (Schneider and Aristodemou, 2025a) and the Transition Action Plan for Consumer Associations (Schneider and Aristodemou, 2025b), knowledge gaps and misinformation continue to hinder acceptance and responsible uptake of innovations such as new genomic techniques (NGTs) and their microalgae-based applications.

For the industry, education on blue biotechnology is essential to bridge scientific advances and market implementation. As highlighted in the Food Industry TAP, limited awareness of NGTs, evolving regulatory frameworks, and sustainability metrics creates uncertainty that discourages investment and innovation. Targeted capacity-building and training on the EU's biotechnology strategy and NGT regulation can equip companies to interpret legislation, ensure compliance, and communicate responsibly about biotechnological products. This aligns with the European Commission (2024) recent communication "Building the Future with Nature: Boosting Biotechnology and Biomanufacturing in the EU", which emphasises knowledge transfer and skills development as prerequisites for an innovation-friendly environment.

For consumers, education serves as a foundation for trust-building and resilience against misinformation. The Consumer Association TAP underlines that most citizens still associate NGTs with traditional GMOs and express concern over safety, transparency, and ethical implications. Clear, accessible science communication — using visual explanations, real-life examples such as the environmental benefits of gene-edited microalgae, and participatory dialogue — can enhance scientific literacy and foster informed decision-making. Educational initiatives co-designed with consumer organisations and scientific partners can therefore strengthen both awareness and agency.

5 Recommendations for promoting and improving blue biotechnology education

Despite the increasing significance of BBE, the field faces several challenges that restrict its wider acceptance and integration into educational systems. In our proposed SWOT analysis (Table 3), we highlight the main strengths, weaknesses, opportunities, and threats associated with BBE that will influence its future.

5.1 Quality of basic education and better integration of studies

In the context of BBE, there is a need to improve science education at the primary and secondary school levels. The field of BB requires a strong foundation in STEM and innovations starting from primary and secondary schools. This allows later students to acquire specific knowledge and skills in complex BB and related fields. By improving science education and encouraging STEM subjects, schools and universities can help create a future workforce that explores and contributes to the rapidly changing

TABLE 3 SWOT analysis of BBE in Europe.

Strengths	Weaknesses
• A shared interest in BBE • The trend among new generations for being closer to nature and more eco-friendly • Importance of sustainable development • Innovative programs and educators • EU and national policies • International BB tertiary education provided by networks • BBE contributes to skilled workforce development for the emerging blue bioeconomy • Access to strong research infrastructure in the EU	• Misconceptions of BBE • Unequal education priorities • Lower awareness in regions without a strong maritime identity • Lack of communication and cooperation between education and industry • Lack of biotechnology inclusion at the secondary school level • Lack of ocean literacy culture • Skill gaps between the education offered and the labour market needs • Lack of awareness of career opportunities in the blue economy • Tertiary BB education networks are not sustaining after the fund expires • Administrative burden and bureaucracy in education–industry collaboration
Opportunities	**Threats**
• Collaboration in BBE • Communication through BBE • Awarness-raising through BBE • Development of the BBE network • Harmonisation of BB postgraduates programs in Europe • Development of smart specialisation strategies • Possibilities of scholarships for students • Opportunity to expand online BBE resources • Initiatives dedicated to professionals • Linking BBE activities with the GDP of biotechnology in the region/country • STEM as a platform for engagement in BBE • Growth of blue bioeconomy sectors creates demand for new curricula and training • Developing lifelong learning pathways for upskilling professionals	• Unstable and limited duration of funding opportunities • Social poverty • Unstable geopolitical situations • Regulatory fragmentation (CBD/Nagoya, ABS, GMO legislation) may hinder innovation, collaboration, and technology transfer • The gaps between the local situation and the European strategy • Brain drain: skilled graduates moving to non-EU markets • Overregulation slowing innovation or commercialization

field of BB. BBE must include multidisciplinary topics, from genetics, (micro)biology, omics technologies, applied research (such as biorefineries, scaling up) targeted to sectors (i.e., pharmacy, agriculture, food/feed, aquaculture), marine natural products chemistry, analytics, to sustainability (techno-economic, social, environmental), legal courses, integrity, the use of artificial intelligence and communication. Although many BB-related programs already include several of these topics, they often remain fragmented and insufficiently integrated. For example, translational failures in red biotechnology occur when promising basic research does not become clinically useful not only due to fragmented expertise, funding models that reward discovery over implementation, but also to a lack of regulatory and translational literacy (Abou-El-Enein et al., 2017; Seyhan, 2019). Many scale-up failures in white biotechnology result not from biological limitations but from educational gaps in real-world process constraints, including oxygen transfer, contamination control, energy use, and economic feasibility (Delebecque and Philp, 2019). BB faces a similar disconnect: students are often trained to isolate marine organisms, identify bioactive compounds, or characterise microbial communities, but receive little preparation for scaling those discoveries into real-world applications, such as sustainable aquaculture, marine bioremediation, or industrial bioproducts. Moreover, the inherently interdisciplinary nature of BB and the time and financial restrictions during the development of new products, often leave out some important milestones, such as sustainability considerations (environmental, economic and social) for production, yield improvement, and preparation of students for careers outside academia, and mentors are often less familiar with career choices in the non-academic world (Kam and Chambers, 2023; Daniotti and Re, 2021). As a result, innovative marine-based solutions remain at the laboratory scale because graduates lack competencies in the regulatory environment, environmental impact assessment, bioengineering, or stakeholder engagement.

5.2 The need for lifelong learning and ocean (formal, non-formal and informal) education

BB demonstrates the need for lifelong learning and comprehensive ocean education across formal, non-formal, and informal settings. Developing and using innovations in the BB field requires regularly updating skills and understanding, staying aware of new developments and improving skills through workshops, seminars, or online courses. Ocean education, both formal and informal, is also very important, especially in BB, as it improves awareness of the healthy ocean and the benefits and importance of using it sustainably. To facilitate this, educational institutions and stakeholders can introduce credit-based industry-aligned training, promote university–industry partnerships, and create shared learning platforms (e.g., digital repositories, remote laboratories, or open science training programs), that have been successfully implemented in other program curricula (Gamage and Dehideniya, 2025; Iyer and Fitzgibbon, 2009). Additionally, integrating internships, research placements, and citizen-science initiatives can help bridge academic knowledge with practical experience, while policy-makers can support those initiatives through financial support, micro-credential systems, and recognition of prior learning.

5.3 Establishing collaborative ocean education networks

The successful development of a motivated and collaborative BBE network depends on several key factors: clearly defining the participants in ocean education, possessing the skills for effective coordination, planning implementation strategies, and securing permanent funding at both local and global levels.

Organisations like COSEE-Ocean (2025) (Centers for Ocean Sciences Education Excellence) and EMSEA (2025) (European Marine Science Educators Association) serve as valuable networks that promote ocean literacy and collaborate with scientists, educators, policymakers, and the public to enhance education and awareness about marine science. Such networks can focus on specific areas, for example, the EMSEA-MED aims to promote Mediterranean Sea Literacy (MSL) (Mokos et al., 2022). Smart Specialisation Strategies (S3) focus on regional features and their connections to innovation and investment, drawing on local assets and resources (European Commission, 2025). S3 serves as a helpful tool for regional research plans and innovation programs, particularly in the Blue Bioeconomy and biotechnology. It uses a participatory approach that includes researchers, investors, and policymakers (Doussineau, 2020). In the EU-funded Horizon 2020 MARINA project, mutual learning workshops involving scientists, citizens, policymakers, and industry stakeholders pointed out the need for locally established BB centres. These centres, created through close collaboration between universities, schools, and industry, would be supported by specific public policies (Ferri et al., 2018; Schneider et al., 2018).

Teaching methods and school programs need to keep changing to meet the needs of today's job market, particularly in the growing blue economy sector. To make this happen, schools and businesses should work together to create training and learning opportunities that people can use throughout their lives. Technology also plays an important role—it can connect education with real-world work and research by offering new tools and learning methods (Selwyn, 2012). This requires the formation of multidisciplinary collaborative networks capable of delivering innovative solutions and commercially viable products that contribute to the circular bioeconomy. An example is the COST Action CA18238 Ocean4Biotech (2025) – European Transdisciplinary Networking Platform for Marine Biotechnology, which has since evolved into a professional association open to anyone with an interest in blue biotechnology (Rotter et al, 2020; Rotter et al., 2021).

5.4 Joint education programs, ensuring sustainability and continuity

As illustrated by the above examples, joint Master's or PhD programs in BB can offer students a diverse range of expertise and resources, enabling them to gain a deeper understanding of BB from multiple academic and cultural perspectives. This approach provides access to a larger network of expertise, research facilities, and industry connections, which are especially valuable in BB, as students have the opportunity to work with diverse marine environments and technologies, while also gaining new perspectives. However, to sustain these programs, strong partnerships between institutions are needed, along with supportive policies and stable funding, particularly to support student and researcher exchanges and shared facilities.

5.5 Harmonisation of blue biotechnology postgraduates in Europe

Another aspect to be considered with BB is geography. Generally, BB is concentrated in Europe's coastal regions. A closer look at Europe reveals that non-coastal EU regions also specialise in the development of microalgae and bioactive compounds from marine bioresources (Doussineau, 2020). This illustrates that the need for education is not limited to Europe's coastal regions. Interest in BB outside coastal areas is often lower due to several factors: the absence of direct contact with marine ecosystems, lower regional investment in marine-focused R&D, fewer industry possibilities related to BB, and lower political prioritisation of ocean-related sectors in regional strategies. These conditions may create a perception that BB is geographically or economically irrelevant to non-coastal regions, contributing to the "apathy" seen in policy discussions and stakeholder engagement. Recognising and addressing these barriers is essential, as similar dynamics are observed in CBD implementation and negotiations, where countries lacking immediate access to marine resources often show reduced engagement despite being affected by regulatory outcomes (Sebuliba, 2024; Vadrot et al., 2022).

5.6 Linking education communities, research and industry

To remain aligned with labour market demands, the curricula and teaching methods in BBE must continually evolve in response to advancements in the biotechnology industry. BBE must include more practical, hands-on activities, and this includes not only formal education and work positions but also ongoing learning supported by the latest educational technologies.

Interdisciplinary collaboration between education, research, and industry can provide more opportunities. For example, Ocean4Biotech is a networking platform that connects and enables collaboration between different stakeholders across BB. Another example is innovation ecosystems, such as the AlgaeProBanos (2025) initiative, which brings together education providers, researchers, technology platforms, companies, and incubators. This initiative can boost activity, ensuring that BB remains visible as a marine-related initiative while generating sustainable solutions for society.

Within the RRI Roadmap^{TM} framework (Schneider, 2019), education functions as an instrument of empowerment and co-creation, rather than a one-way dissemination tool. Integrating structured learning into participatory processes reinforces reflexivity, transparency, and long-term trust in science-policy interactions. Consequently, embedding continuous education for industry and consumers into the governance of blue biotechnology supports responsible innovation, societal readiness, and alignment with the updated EU Bioeconomy Strategy, the forthcoming European Biotech Act, and the UN Ocean Decade objectives.

5.7 Entrepreneurship training

To support innovations, BBE programs should integrate entrepreneurship-focused elements, such as business training and planning, courses on intellectual property, and collaboration with existing SMEs. SMEs play an important role in transforming research into usable products—such as bio-based materials or food technologies. These programs may also offer mentorship, internships, and access to incubators or accelerators, providing students and researchers with the tools and support needed to transform innovative ideas into practical solutions coming from BB. For example, the Blue Bio Value Ideation and Acceleration programs in Portugal bridge BB research and entrepreneurship, enabling scientific teams to translate research outcomes into viable market solutions (Blue Bio Value, 2023). Since 2018, these initiatives have supported the creation of 77 BB start-ups.

5.8 Adjust funding at the national or regional level and link BBE activities to the biotechnology GDP of the region or country

Assessing and modifying funding allocation mechanisms is very important to support BBE and BB research. Limited national funding, aside from policy support and education, was identified as the main bottleneck preventing the advancement of innovation in the field of BB in the Northern Mediterranean region (Rotter et al., 2023). Linking BBE funding to the performance of the biotech sector, for example, by examining its economic impact or its share of GDP, could be the way to go. This is important because economic and educational strategies often connect to the specific features and goals of different geographic areas. Biotechnology development varies across EU regions, with different resources and priorities, and to strengthen the blue bioeconomy in the EU, a cohesive strategy is needed—one that integrates education with industry needs. Aligning education with BB can drive innovation, create quality jobs, attract investment, and boost Europe's global competitiveness in biotechnology.

Author contributions

MK: Project administration, Funding acquisition, Resources, Data curation, Conceptualization, Methodology, Writing – original draft. AT-S: Investigation, Conceptualization, Writing – review & editing, Writing – original draft. DO: Writing – review & editing, Investigation, Writing – original draft, Conceptualization, Funding acquisition, Visualization, Data curation, Formal analysis. LLB: Investigation, Conceptualization, Writing – review & editing, Writing – original draft, Funding acquisition. SPG: Conceptualization, Investigation, Writing – review & editing, Writing – original draft, Funding acquisition. LG: Writing – review & editing, Investigation, Data curation. NN: Writing – review & editing, Writing – original draft, Conceptualization, Investigation. JC: Investigation, Writing – review & editing, Visualization. IM: Writing – original draft, Conceptualization, Writing – review & editing. AR: Writing – original draft, Funding acquisition, Conceptualization, Writing – review & editing. XT: Writing – original draft, Writing – review & editing, Conceptualization. BKS: Investigation, Writing – review & editing, Writing – original draft. SB-J: Investigation, Writing – review & editing.

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Author XT was employed by XPRO Consulting Limited.

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References

Abou-El-Enein, M., Duda, G. N., Gruskin, E. A., and Grainger, D. W. (2017). Strategies for derisking translational processes for biomedical technologies. *Trends Biotechnol.* 35, 100–108. doi: 10.1016/j.tibtech.2016.07.007

Alberro, A., Ortega-Lasuen, U., and Díez, J. R. (2023). Current knowledge and attitudes of students towards biotechnology: A long way to go. *IKASTORRATZA. e-Revista de Didáctica* 30, 1–25. 10.37261/30_alea/1

AlgaeProBanos (2025). Accelerator (Berlin, Germany: AlgaeProBanos). Available online at: https://algaeprobanos.eu/accelerator/.

Andersson, K., and Gullberg, A. (2014). What is science in preschool and what do teachers have to know to empower children? *Cultural Stud. Sci. Educ.* 9, 275–296. doi: 10.1007/s11422-012-9439-6

Andrzejewska-Górecka, D., Drożdż, M., Liebers, D., Meissner, Z., and Nowak, K. (2020). Biotechnologiczny skok w przyszłość czy dryf? Polska potrzebuje strategii rozwoju biotechnologii (Polski Instytut Ekonomiczny, Al. Jerozolimskie 87, 02-001 Warszawa, Poland: Polski Instytut Ekonomiczny). Available online at: https://pie.net.pl/wp-content/uploads/2020/06/PIE-Raport_Biotech.pdf.

Avdispahicć, M., Baker, J. Y., Di Dio, R., Kramer, S. L., Loewenstern, V., and Lukicć Bilela, L. (2018a). Operativne smjernice za implementaciju Operativnog nastavnog plana I programa (ONPP) za STEM kompetencije. (Sarajevo: Save the Children International), 1–46.

Avdispahicć, M., Baker, J. Y., Di Dio, R., Kramer, S. L., Loewenstern, V., and Lukicć Bilela, L. (2018b). Priručnik za obuku/osposobljavanje nastavnika u primjeni Operativnog nastavnog plana i programa za STEM kompetencije. (Sarajevo: Save the Children International), 1–323.

Avdispahicć, M., Miller, L., and Smajlovicć, L. (2018c). Nacrt Operativnog nastavnog plana i programa (ONPP) za STEM kompetencije zasnovanog na ZJNPP definiranoj na ishodima učenja - matematika. (Sarajevo: Save the Children International), 1–449.

BBMBC (2023). BBMBC: From a blue career project to a Mundus master (Brussells: European Commission). Available online at: https://oceans-and-fisheries.ec.europa.eu/news/bbmbc-blue-career-project-mundus-master-2023-04-21_en.

Beck, E. (2019). Access and benefit sharing—-The perspective of basic research. *Phytomedicine* 53, 302–307. doi: 10.1016/j.phymed.2018.10.018

BIC (2019). Joint industry vision for a circular biosociety in 2050 (Brussells: Bio-based Industries Consortium). Available online at: https://www.biconsortium.eu/publication/joint-industry-vision-circular-biosociety-2050.

Biotech Act (2024). The European Biotech Act (Brussells: NCP Brussels). Available online at: https://ncp.brussels/the-european-biotech-act/.

BlueBioMatch (2025). Home (BlueBioMatch). Available online at: https://bluebiomatch.hivebrite.com/.

BlueBioTechPreneurs (2025). Home (BlueBioTechPreneurs). Available online at: https://bluebiotechpreneurs.eu/.

Blue Bio Value (2023). Ideation 2023. (Lisbon, Portugal: Blue Bio Value). Available online at: https://www.bluebiovalue.com/ideation/ideation-2023/.

BlueGeneration (2025). Home (BlueGeneration). Available online at: https://www.bluegeneration.org/index.php/en/.

Bluepartnership (2025). Sustainable Blue Economy Partnership's first joint transnational call. Available online at: https://bluepartnership.eu/funding-opportunity/sustainable-blue-economy-partnerships-first-joint-transnational-call (Accessed March 6, 2025).

Caruso, G., Floris, R., Serangeli, C., and Di Paola, L. (2020). Fishery wastes as a yet undiscovered treasure from the sea: biomolecules sources, extraction methods and valorization. *Mar. Drugs* 18, 622. doi: 10.3390/md18120622

Catalog of Best STEM Practice. (2020). Selected Lesson Plan Examples for Integrated STEM Teaching / Katalog dobrih STEM praksi: Odabrani primjeri izrade najboljih pripremnih časova za integrirano STEM podučavanje. *Save the Children, Program za sjeverozapadni Balkan*, pp. 1–133 Available online at: https://drive.google.com/file/d/10U6I-ANywy7hRigdR05QC2LHJWW1zjC8/view (Accessed February 6, 2026).

Cava, F., Schoedinger, S., Tuddenham, P., and Strang, C. (2005). Science content and standards for ocean literacy: A report on ocean literacy, 1-50. doi: 10.13140/RG.2.2.12126.84804

Chirivella-Martorell, J. (2023). "Academic research integration: A teaching tool useful for boosting multidisciplinary research teams on marine biotechnology," in *Book of Abstracts. EU-CONEXUS Research Conference – Aquatic and Coastal Ecosystems: Challenges and Opportunities Towards Sustainable Development* (EU-CONEXUS, Valencia, Spain), 54. Available online at: https://www.eu-conexus.eu/wp-content/uploads/2024/02/v4.Book-of-Abstracts_Scientific-Committee_-EU-CONEXUS-Research-Conference.pdf.

Ciência Viva (2025). Home (Lisbon, Portugal: Ciência Viva). Available online at: https://www.cienciaviva.pt/.

CMMI (2016). CMMI CYPRUS Marine and Maritime Institute. Available online at: https://www.cmmi.blue/ (Accessed March 6, 2025).

COM (2012). Blue Growth — opportunities for marine and maritime sustainable growth, Communication COM/2012/494 final. Available online at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52012DC0494.

COM (2019). Communication on the European Green Deal (Brussels, Belgium: European Commission). Available online at: https://commission.europa.eu/document/daef3e5c-a456-4fbb-a067-8f1cbe8d9c78_en.

COM (2021). Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the

Regions on a new approach for a sustainable blue economy in the EU: Transforming the EU's blue economy for a sustainable future (Brussels, Belgium: European Commission). Available online at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021DC0240.

COM (2025). Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: A Strategic Framework for a Competitive and Sustainable EU Bioeconomy (Brussels, Belgium: European Commission). Available online at: https://environment.ec.europa.eu/document/download/dbf8d2ba-9332-4f7a-b336-f356fa4b7236_en?filename=COM_2025_960_1_EN_ACT_part1_v10_0.pdf.

CORDIS (2017). Marine and Maritime Research, Innovation, Technology Centre of Excellence. CORDIS – EU Research Results. https://cordis.europa.eu/project/id/763815 (Accessed March 6, 2025).

Commonwealth (2024). Commonwealth and Cyprus sign MOU on Blue Charter Centre of Excellence. https://thecommonwealth.org/news/commonwealth-and-cyprus-sign-mou-blue-charter-centre-excellence (Accessed September 19, 2025).

COSEE-Ocean (2025). Home (New Jersey, United States: COSEE Ocean Network). Available online at: http://coseeocean.net.

Costa, R. L., and Faria, C. (2025). The Blue School Program: A model for holistic ocean literacy education. *Sustainability* 17, 661. doi: 10.3390/su17020661

Cyprus University of Technology (2025). Cyprus university of technology. Available online at: https://www.cut.ac.cy/?languageId=1 (Accessed March 6, 2025).

Daniotti, S., and Re, I. (2021). Marine biotechnology: Challenges and development market trends for the enhancement of biotic resources in industrial pharmaceutical and food applications. A statistical analysis of scientific literature and business models. *Mar. Drugs* 19, 61. doi: 10.3390/md19020061

de la Hoz, M. C., Solé-Llussà, A., Haro, J., et al. (2022). Student Primary Teachers' Knowledge and Attitudes Towards Biotechnology—Are They Prepared to Teach Biotechnological Literacy?. *Journal of Science Education and Technology* 31, 203–216. 10.1007/s10956-021-09942-z

Delebecque, C. J., and Philp, J. (2019). Education and training for industrial biotechnology and engineering biology. *Eng. Biol.* 3, 6–11. doi: 10.1049/enb.2018.0001

Deloitte, empirica and Fondazione Giacomo Brodolini (2022). Promoting education, training and skills in the bioeconomy: Final report (Luxembourg: Publications Office of the European Union). Available online at: https://biobec.eu/wp-content/uploads/2022/10/promoting-education-training-skills-in-the-bioeconomy.pdf.

Desbois, A. P., Margarit, A. L., Chirivella, J., McKenzie, D., Leão, P., and Bordenave-Juchereau, S. (2019). *Masters-level skills and attributes valued by employers in blue biotechnology and aquaculture* (Poster presentation for BMBC project meeting).

DGES (2025a). Pesquisa de cursos e instituições. Lisabon, Portugal. Available online at: https://www.dges.gov.pt/pt/pesquisa_cursos_instituicoes (Accessed August 7, 2025).

DGES (2025b). Guias (Lisabon, Portugal: IndCurso). Available online at: https://www.dges.gov.pt/guias/indcurso.asp.

Doussineau, M. (2020). Smart *sp*ecialisation and blue biotechnology in Europe (Luxembourg: Publications Office of the European Union). doi: 10.2760/19274

Duarte, C. M., Wu, J., Xiao, X., Bruhn, A., and Krause-Jensen, D. (2017). Can seaweed farming play a role in climate change mitigation and adaptation? *Front. Mar. Sci.* 4. doi: 10.3389/fmars.2017.00100

Eckerstorfer, M. F., Dolezel, M., Miklau, M., Greiter, A., Heissenberger, A., Kastenhofer, K., et al. (2025). Environmental applications of GM microorganisms: tiny critters posing huge challenges for risk assessment and governance. *Int. J. Mol. Sci.* 26, 3174. doi: 10.3390/ijms26073174

Edmeades, S., Jug-Dujakovic, J., Bajic, B., and Bilandzija, J. (2021). Croatia – Beyond the pond: A vision and roadmap for the strategic transformation of the aquaculture sector – 2020–2030 (World Bank). Available online at: https://documents.worldbank.org/en/publication/documents-reports/documentdetail/en/519271623382044799.

EIMIN (2023). Lietuvos gyvybės mokslų sektoriaus kelrodis. Available online at: https://eimin.lrv.lt/uploads/eimin/documents/files/Gyvybe%CC%87s%20mokslu%CC%A8%20sektoriaus%20kelrodis(1).pdf (Accessed August 7, 2025).

EMSEA (2025). Home (Gent, Belgium: EMSEA). Available online at: http://www.emsea.eu/default.php.

ENABLE_BIH: ANNUAL NARRATIVE REPORT (2020). Save the Children International. Available online at: https://www.scribd.com/document/735899527/PA00X9Z8 (Accessed April 23, 2025).

Escola Azul (2025). Home (Algés, Portugal: Escola Azul). Available online at: https://escolaazul.pt/en.

EU-CONEXUS (2025). Who we are. Available online at: https://www.eu-conexus.eu/en/home/who-we-are/ (Accessed August 7, 2025).

European Commission (2012). Blue Growth — opportunities for marine and maritime sustainable growth. Communication COM/2012/494 final. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52012DC0494.

European Commission (2024). Building the Future with Nature: Boosting Biotechnology and Biomanufacturing in the EU. Available online at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52024DC0137 (Accessed April 23, 2025).

European Commission (2025). About | S3 Community of Practice. Available online at: https://ec.europa.eu/regional_policy/policy/communities-and-networks/s3-community-of-practice/about_en (Accessed March 10, 2025).

European Commission (EC) (2016). Commission invests over €7.5 million for blue growth and jobs. Available online at: https://documents.worldbank.org/en/publication/documents-reports/documentdetail/519271623382044799 (Accessed April 5, 2025).

European Commission (EC) (2025). Skills and career development. Available online at: https://oceans-and-fisheries.ec.europa.eu/ocean/blue-economy/skills-and-career-development_en (Accessed April 5, 2025).

European Marine Board (EMB) (2017). Marine biotechnology: Advancing innovation in Europe's bioeconomy. Available online at: https://marineboard.eu/sites/marineboard.eu/files/public/publication/EMB_Policy_Brief_4_Marine_Biotechnology_Web.pdf (Accessed August 7, 2025).

Falkner, R. (2000). Regulating biotech trade: the Cartagena Protocol on biosafety. *Int. Affairs.* 76, 299–313. doi: 10.1111/1468-2346.00135

Feden, P.D., Husremović, Dž., Kasumagić-Kaledžić, L., Merlino, F.J., Oswald, M., and Zečević, I. (2018a). Standard kvalifikacije za pedagoško – psihološko – didaktičko – metodičko obrazovanje nastavnika na univerzitetima u Bosni i Hercegovini. (Sarajevo: Save the Children International), pp. 1–19.

Feden, P.D., Husremović, Dž., Kasumagić-Kaledžić, L., Merlino, F.J., Oswald, M., and Zečević, I. (2018b). Smjernice za primijenu standarda kvalifikacije za pedagoško – psihološko – didaktičko – metodičko obrazovanje nastavnika na univerzitetima u Bosni i Hercegovini. (Sarajevo: Save the Children International), pp. 1–38.

Feden, P.D., Merlino, F.J., and Oswald, M. (2018c). Priručnik za univerzitetske nastavnike. (Sarajevo: Save the Children International), pp. 1–61.

Ferri, F., Biancone, N., Bicchielli, C., Caschera, M. C., D'Andrea, A., D'Ulizia, A., et al. (2018). "The MARINA project: Promoting responsible research and innovation to meet marine challenges," in *Governance and sustainability of responsible research and innovation processes: Cases and experiences*. Ed. F. Ferri, et al (Springer, Cham), 71–81. doi: 10.1007/978-3-319-73105-6_10

Forleo, M. B., and Bredice, M. (2024). What is the consciousness, literacy and behaviour of Italian Gen-Z towards the protection of the marine environment? *Mediterr. Mar. Sci.* 25, 768–782. doi: 10.12681/mms.37222

French, V., Kellett, P., Delany, J., and McDonough, N. (2017). Advancing citizen science for coastal and ocean research (Ostend, Belgium: European Marine Board). Available online at: https://www.marineboard.eu/sites/marineboard.eu/files/public/publication/EMB_PP23:Citizen_Science_web.pdf.

Gallego, I., Medic, N., Skov Pedersen, J., Ramasamy, P. K., Robbens, J., Vereecke, E., et al. (2025). The microalgal sector in Europe: Towards a sustainable bioeconomy. *New Biotechnol.* 86, 1–13. doi: 10.1016/j.nbt.2025.01.002

Gamage, K. A., and Dehideniya, S. C. (2025). Unlocking career potential: how micro-credentials are revolutionising higher education and lifelong learning. *Educ. Sci.* 15, 525. doi: 10.3390/educsci15050525

Gaudêncio, S. P., Bayram, E., Lukić Bilela, L., Cueto, M., Díaz-Marrero, A. R., Haznedaroglu, B. Z., et al. (2023). Advanced methods for natural products discovery: Bioactivity screening, dereplication, metabolomics profiling, genomic sequencing, databases and informatic tools, and structure elucidation. *Mar. Drugs* 21, 308. doi: 10.3390/md21050308

Geuer, L., Erdmann, N., Kollmen, J., Otteny, A., Wastian, K., Wallrath, S., et al. (2025). Educational approaches to bioprocess engineering using DIY bioreactors for scientific literacy. *Educ. Sci.* 15 (3), 323. doi: 10.3390/educsci15030323

Global Environment Facility (GEF) (2018). Blue economy. Available online at: https://www.thegef.org/sites/default/files/publications/GEF%20Assembly_BlueEconomy%20Factsheet_6.19.18.pdf (Accessed May 11, 2025).

Gov.pl (2021). National Recovery Plan – We are programming EU funds for Poland (Warsaw, Poland: Ministry of Development Funds and Regional Policy). Available online at: https://www.gov.pl/web/funds-regional-policy/national-recovery-plan—we-are-programming-eu-funds-for-Poland.

Haaf, A., Hofmann, S., and Schüler, J. (2021). Measuring the economic footprint of the biotechnology industry in Europe. *Ind. Biotechnol.* 17, 117–124. doi: 10.1089/ind.2021.29249.aha

Hossain, S., and Tan, J. L. (2024). Fostering bio-entrepreneurship education in an evolving industry: Insights from teachers and recent graduates. *J. Commercial Biotechnol.* 29, 173–185. doi: 10.5912/jcb2219

Human Resource Development Authority (HRDA) (2016). Cyprus – Identification of blue skill needs in the Cyprus economy 2016–26 (Thessaloniki: CEDEFOP). Available online at: https://www.cedefop.europa.eu/en/news/Cyprus-identification-blue-skill-needs-Cyprus-economy-2016-26.

ICCROM (2016). Access and Benefit-Sharing (Nagoya Protocol and the CBD) (Rome, Italy: ICCROM – Our Collections Matter). Available online at: https://ocm.iccrom.org/index.php/documents/access-and-benefit-sharing-nagoya-protocol-and-cbd.

IMBRSea (2025). Home (Ghent, Belgium: IMBRSea). Available online at: https://www.imbrsea.eu/.

Invest Lithuania (2025). Life sciences in Lithuania. Available online at: https://investLithuania.com/wp-content/uploads/Life-Sciences-in-Lithuania.pdf (Accessed April 23, 2025).

IRB (2025). BioProCro – Scientific Center of Excellence | Laboratory for Aquaculture Biotechnology. Available online at: https://www.irb.hr/eng/Divisions/Division-of-Materials-Chemistry/Laboratory-for-aquaculture-biotechnology/Projects/BioProCro-Scientific-Center-of-Excellence (Accessed April 23, 2025).

Iyer, R. S., and Fitzgibbon, W. E. (2009). Building the future biotechnology workforce: A University of Houston model. *J. Commercial Biotechnol.* 15, 171–182. doi: 10.1057/jcb.2008.59

Jimenez, P. C., Wilke, D. V., Branco, P. C., Bauermeister, A., Rezende-Teixeira, P., Gaudêncio, S. P., et al. (2020). Enriching cancer pharmacology with drugs of marine origin. *Br. J. Pharmacol.* 177, 3–27. doi: 10.1111/bph.14876

Johnson, K., Masters, I., and Dalton, G. (2018). *Building industries at sea: "Blue growth" and the new maritime economy*. Taylor & Francis, London.

Kafarski, P. (2012). Rainbow code of biotechnology. *Chemik* 66, 814–816. https://www.researchgate.net/publication/287253802_Rainbow_code_of_biotechnology.

Kam, K., and Chambers, T. (2023). Transitioning to a career outside of academia: A short guide for students and early career researchers. *Oceanography* 37, 160–162. doi: 10.5670/oceanog.2023.304

Kataržytė, M., Hille, S., and Terlecka, R. (2017). Promoting marine science: international science camp as a platform. *Marine Policy* 84, 76–81. 10.1016/j.marpol.2017.07.013

Kelly, R., Evans, K., Alexander, K., Bettiol, S., Corney, S., Cullen-Knox, C., et al. (2022). Connecting to the oceans: supporting ocean literacy and public engagement. *Rev. Fish Biol. Fisheries* 32, 123–143. doi: 10.1007/s11160-020-09625-9

Klaipėda City Municipality (n.d.). Klaipėda 2030 Strategy. https://keps2030.klaipeda.lt/en/strategy (Accessed February 4, 2026).

Klaipėda Region Development Council (2021). Klaipėda Region Specialisation Strategy 2030. https://klaipedaregion.lt/wp-content/uploads/2021/09/KR-SS-2030_final_ENG.pdf (Accessed February 4, 2026).

Larimore, R. A. (2020). Preschool science education: A vision for the future. *Early Childhood Educ. J.* 48, 703–714. doi: 10.1007/s10643-020-01033-9

Livingstone, D. W. (1999). Exploring the icebergs of adult learning: Findings of the first Canadian survey of informal learning practices. *Can. J. Study Adult Educ.* 13, 49–72. doi: 10.56105/cjsae.v13i2.2000

Luiten, E. E. M., Akkerman, I., Koulman, A., Kamermans, P., Reith, H., Barbosa, M. J., et al. (2003). Realizing the promises of marine biotechnology. *Biomolecular Eng.* 20, 429–439. doi: 10.1016/S1389-0344(03)00074-1

Lukić Bilela, L., and Muratović, E. (2018). Nacrt Operativnog nastavnog plana i programa (ONPP) za STEM kompetencije zasnovanog na ZJNPP definiranoj na ishodima učenja - biologija. (Sarajevo: Save the Children International), pp. 1–721.

Maiser, E., Horbelt, J., Thoma, M., Baumgarten, Y., Colosimo, B., Penttilä, M., et al. (2022). Biointelligent manufacturing – Definitions, international status, potentials for Europe and recommendations: The White Paper. pp. 1-48. doi: 10.24406/publica-607

Maksimović, M. (2018). Nacrt Operativnog nastavnog plana i programa (ONPP) za STEM kompetencije zasnovanog na ZJNPP definiranoj na ishodima učenja - kemija. (Sarajevo: Save the Children International), pp. 1–549.

MEASURE-BIH (2018). Brief assessment of basic education in Bosnia and Herzegovina – The follow-on: Final report. Available online at: https://measurebih.com/uimages/MEASURE-BiH20BEA20Follow-on20Assessment20Final.pdf (Accessed March 6, 2024).

MedAlgae (2016). Production of biodiesel from algae in selected Mediterranean countries (Barcelona, Spain: Mediterranean Blue Economy Stakeholder Platform). Available online at: https://medblueconomyplatform.org/vkc/projects/production-of-biodiesel-from-algae-in-selected-mediterranean-countries-cfc4cf3cad/.

Minister of Science and Higher Education (2018). Regulation of 20 September 2018 on fields of science and scientific disciplines as well as artistic disciplines. *Journal of Laws of the Republic of Poland*, 2018, item 1818.

Minister of Education and Science (2022). Regulation of 11 October 2022 on fields of science and scientific disciplines as well as artistic disciplines. *Journal of Laws of the Republic of Poland*, 2022, item 2202.

Ministry of Science and Higher Education / RAD-on (2024). Students 2024 Report. Available online at: https://radon.nauka.gov.pl/raporty/studenci_2024 (Accessed January 1, 2023).

Minister of Education and Science (2025). Announcement of 12 February 2025 on the consolidated text of the regulation on fields of science and scientific disciplines as well as artistic disciplines. *Journal of Laws of the Republic of Poland*, 2025.

Mokos, M., De-Bastos, E., Realdon, G., Wojcieszek, D., Papathanasiou, M., and Tuddenham, P. (2022). Navigating ocean literacy in Europe: 10 years of history and future perspectives. *Mediterr. Mar. Sci.* 23, 277–288. doi: 10.12681/mms.26989

Mrdović, S. (2018). Nacrt Operativnog nastavnog plana i programa (ONPP) za STEM kompetencije zasnovanog na ZJNPP definiranoj na ishodima učenja IT. (Sarajevo: Save the Children International), pp. 1–797.

Ocean4Biotech (2025). Home (Piran, Slovenia: Ocean4Biotech). Available online at: https://www.ocean4biotech.eu/.

OECD (2015). Enabling the Next Production Revolution: Issues Paper (DSTI/IND (2015)2) (Paris: OECD Publishing). Available online at: https://one.oecd.org/document/DSTI/IND(2015)2/en/pdf.

OECD (2016). *The Ocean Economy in 2030* (Paris: OECD Publishing). doi: 10.1787/9789264251724-en

Paš, M., Vogrinc, J., Raspor, P., Udovč Knežević, N., and Čehovin Zajc, J. (2019). Biotechnology learning in Slovenian upper-secondary education: Gaining knowledge and forming attitudes. *Res. Sci. Technol. Educ.* 37, 110–125. doi: 10.1080/02635143.2018.1491473

Pérez-López, P., Feijoo, G., and Moreira, M. T. (2018). "Sustainability assessment of blue biotechnology processes: Addressing environmental, social and economic dimensions," in *Designing sustainable technologies, products and policies: From science to innovation*. Eds. E. Benetto, K. Gericke and M. Guiton (Cham, Switzerland: Springer), 475–486. doi: 10.1007/978-3-319-66981-6_53

Persano Adorno, D., Mallahnia, T., Koch, V., Zailskaitė-Jakštė, L., Ostreika, A., Urbaitytė, A., et al. (2021). The BioS4You European project: An innovative way to effectively engage Z-generation students in STEM disciplines. *Educ. Sci.* 11, 774. doi: 10.3390/educsci11120774

Power, C. N., and Maclean, R. (2013). "Lifelong learning: Meaning, challenges, and opportunities," in *Skills development for inclusive and sustainable growth in developing Asia-Pacific*. Eds. R. Maclean, S. Jagannathan and J. Sarvi (Dordrecht, Netherlands: Springer), 29–42. doi: 10.1007/978-94-007-5937-4_2

Precedence Research (2024). Marine biotechnology market size: Share and trends 2024 to 2034. Available online at: https://www.precedenceresearch.com/marine-biotechnology-market (Accessed April 24, 2025).

Raja, K., Suresh, K., Anbalagan, S., Ragini, Y. P., and Kadirvel, V. (2024). Investigating the nutritional viability of marine-derived protein for sustainable future development. *Food Chem.* 448, 139087. doi: 10.1016/j.foodchem.2024.139087

Rochette, J., Unger, S., Herr, D., Johnson, D., Nakamura, T., Packeiser, T., et al. (2014). The regional approach to the conservation and sustainable use of marine biodiversity in areas beyond national jurisdiction. *Mar. Policy* 49, 109–117. doi: 10.1016/j.marpol.2014.02.005

Rotter, A., Bacu, A., Barbier, M., Bertoni, F., Bones, A. M., Cancela, M. L., et al. (2020). A new network for the advancement of marine biotechnology in Europe and beyond. *Frontiers in Marine Science* 7, 278. 10.3389/fmars.2020.00278

Rotter, A., Barbier, M., Bertoni, F., Bones, A. M., Cancela, M. L., Carlsson, J., et al. (2021). The essentials of marine biotechnology. *Front. Mar. Sci.* 8. doi: 10.3389/fmars.2021.629629

Rotter, A., Giannakourou, A., Argente García, J. E., Quero, G. M., Auregan, C., Triantaphyllidis, G., et al. (2023). Identification of marine biotechnology value chains with high potential in the Northern Mediterranean region. *Mar. Drugs* 21, 416. doi: 10.3390/md21070416

Schneider, X. T. (2019). *The Responsible Research and Innovation (RRI) Roadmap©TM: Methodology* (ResearchGate). doi: 10.13140/RG.2.2.13278.96325

Schneider, X. T., and Aristodemou, E. (2025a). *Action pathway towards New Genomic Techniques (NGTs) in the food industry* (ResearchGate). doi: 10.13140/RG.2.2.36238.63041

Schneider, X. T., and Aristodemou, E. (2025b). *Consumer associations' action pathway towards New Genomic Techniques (NGTs)* (ResearchGate). doi: 10.13140/RG.2.2.19461.41442

Schneider, X., Flavin, N., Breslin, J., and Gault, J. (2018). Applying responsible research and innovation in wave energy – Lessons learned and best practices. Available online at: https://www.researchgate.net/publication/330089935_Applying_Responsible_Research_and_Innovation_in_Wave_Energy-Lessons_Learned_and_Best_Practices (Accessed August 7, 2025).

Schneider, X. T., Stroil, B. K., Tourapi, C., Rebours, C., Gaudêncio, S. P., Novoveska, L., et al. (2022). Responsible research and innovation framework, the nagoya protocol and other european blue biotechnology strategies and regulations: gaps analysis and recommendations for increased knowledge in the marine biotechnology community. *Mar. Drugs* 20, 290. doi: 10.3390/md20050290

Schneider, X. T., Tourapi, C., Rebours, C., Gaudêncio, S. P., Novoveska, L., and Vasquez, M. I. (2023). Improving awareness, understanding, and enforcement of blue biotechnology regulations: new insights and futures ahead. *Trends Biotechnol.* 41, 411–427. doi: 10.1016/j.tibtech.2023.05.011

Schugurensky, D. (2000). The forms of informal learning: towards a conceptualization of the field (Toronto: Centre for the Study of Education and Work, University of Toronto). Available online at: https://tspace.library.utoronto.ca/handle/1807/2733.

Scowcroft, G., Bishop, T., Tuddenham, P., and Gingras, A. (2019). 2019 Global Ocean Science Education Workshop Report (Narragansett, RI: COSEE, University of Rhode Island Graduate School of Oceanography). Available online at: https://www.coexploration.org/gose/2019/2019_Global_Ocean_Science_Education_Workshop_Report.pdf.

Sebuliba, S. (2024). The landlocked ocean: landlocked states in BBNJ negotiations and the impact of fixed land-sea relations in global ocean governance. *Front. Mar. Sci.* 11. doi: 10.3389/fmars.2024.1306386

Secretariat of the Convention on Biological Diversity (2000). Text of the Cartagena Protocol on Biosafety (Montreal: The Biosafety Clearing-House (BCH). Available online at: http://bch.cbd.int/protocol/text.

Secretariat of the Convention on Biological Diversity (2016). Text of the Convention. Available online at: https://www.cbd.int/convention/text (Accessed August 7, 2025).

Selwyn, N. (2012). Making sense of young people, education and digital technology: the role of sociological theory. *Oxford Review of Education* 38 (1), 81–96. doi: 10.1080/03054985.2011.577949

Seyhan, A. A. (2019). Lost in translation: the valley of death across preclinical and clinical divide–identification of problems and overcoming obstacles. *Trans. Med. Commun.* 4, 1–19. doi: 10.1186/s41231-019-0050-7

Shipping Deputy Ministry (2021). Policy statement on maritime spatial planning (Nicosia: Shipping Deputy Ministry, Republic of Cyprus). Available online at: https://www.gov.cy/media/sites/25/2025/01/Policy-Statement-on-MSP.pdf.

Sihvonen, P., Lappalainen, R., Herranen, J., and Aksela, M. (2024). Promoting sustainability together with parents in early childhood education. *Educ. Sci.* 14, 541. doi: 10.3390/educsci14050541

Siry, C., and Kremer, I. (2011). Children explain the rainbow: Using young children's ideas to guide science curricula. *J. Sci. Educ. Technol.* 20, 643–655. doi: 10.1007/s10956-011-9320-5

Submariner (2025). Education & Capacity Building (Berlin, Germany: Submariner Network for Blue Growth). Available online at: https://submariner-network.eu/our-solutions/education-capacity-building/.

Sundberg, B., Areljung, S., Due, K., Ekström, K., Ottander, C., and Tellgren, B. (2016). Understanding preschool emergent science in a cultural historical context through Activity Theory. *Eur. Early Childhood Educ. Res. J.* 24, 567–580. doi: 10.1080/1350293X.2014.978557

Szczygielski, K., Lewkowicz, J., and Michałek, J. J. (2022). The biotechnology sector in a latecomer country: The case of Poland. *New Biotechnol.* 68, 97–107. doi: 10.1016/j.nbt.2022.01.008

Tanović, L. (2018). Nacrt Operativnog nastavnog plana i programa (ONPP) za STEM kompetencije zasnovanog na ZJNPP definiranoj na ishodima učenja - fizika. (Sarajevo: Save the Children International), pp. 1–241.

TechFusion (2025). Life Sciences | Biotech (Vilnius, Lithuania: Vilnius TechFusion). Available online at: https://vilniustechfusion.com/en/life-sciences/.

uBlueTec (2023). uBlueTec – Where skills meet innovation for a sustainable future. https://ubluetec.eu/ (Accessed March 6, 2025).

Udemy (2025). Instructor Profile | sb-focus-project. Available online at: https://www.udemy.com/user/sb-focus-project/ (Accessed April 23, 2025).

United Nations (2023). Agreement on Marine Biological Diversity of Areas Beyond National Jurisdiction (BBNJ Agreement) (New York, USA: UNEP – UN Environment Programme). Available online at: https://www.unep.org/resources/agreement-marine-biological-diversity-areas-beyond-national-jurisdiction-bbnj-agreement.

United Nations (UN) (2015). Transforming our world: the 2030 Agenda for Sustainable Development (New York, USA: Department of Economic and Social Affairs). Available online at: https://sdgs.un.org/2030agenda.

Vadrot, A. B., Langlet, A., and Tessnow-von Wysocki, I. (2022). Who owns marine biodiversity? Contesting the world order through the 'common heritage of humankind' principle. *Environ. Politics* 31, 226–250. doi: 10.1080/09644016.2021.1911442

Vanderschuren, H., Heinzmann, D., Faso, C., Stupak, M., Arga, K. Y., Hoerzer, H., et al. (2010). A cross-sectional study of biotechnology awareness and teaching in European high schools. *New Biotechnology* 27, (6), 822–828. 10.1016/j.nbt.2010.01.338

Vierros, M., and De Fontaubert, C. (2017). The potential of the blue economy: Increasing long-term benefits of the sustainable use of marine resources for small island developing states and coastal least developed countries (Washington, DC: World Bank). Available online at: https://openknowledge.worldbank.org/entities/publication/a36b153d-0284-58b0-b7b3-35a26438f31b.

Vierros, M., Suttle, C. A., Harden-Davies, H., and Burton, G. (2016). Who owns the ocean? Policy issues surrounding marine genetic resources. *Limnology Oceanography Bull.* 25, 29–35. doi: 10.1002/lob.10108

Vincx, M., Degraer, S., Vanaverbeke, J., Vanden Berghe, E., Van Hoey, G., Weslawski, J. M., et al. (2018). Training the 21st century marine professional: A new vision for marine graduate education and training programmes in Europe. Future Science Brief, 2 (Ostend, Belgium: European Marine Board). Available online at: https://www.marineboard.eu/sites/marineboard.eu/files/public/publication/EMB_FSB2_2018_Web_v1.pdf.

Zotti, S. (2022). Education and the european green deal: strengthening sustainability education in the EU. *Int. J. Civil Eng.* 5 (2), p.1. doi: 10.11114/ijce.v5i2.5544